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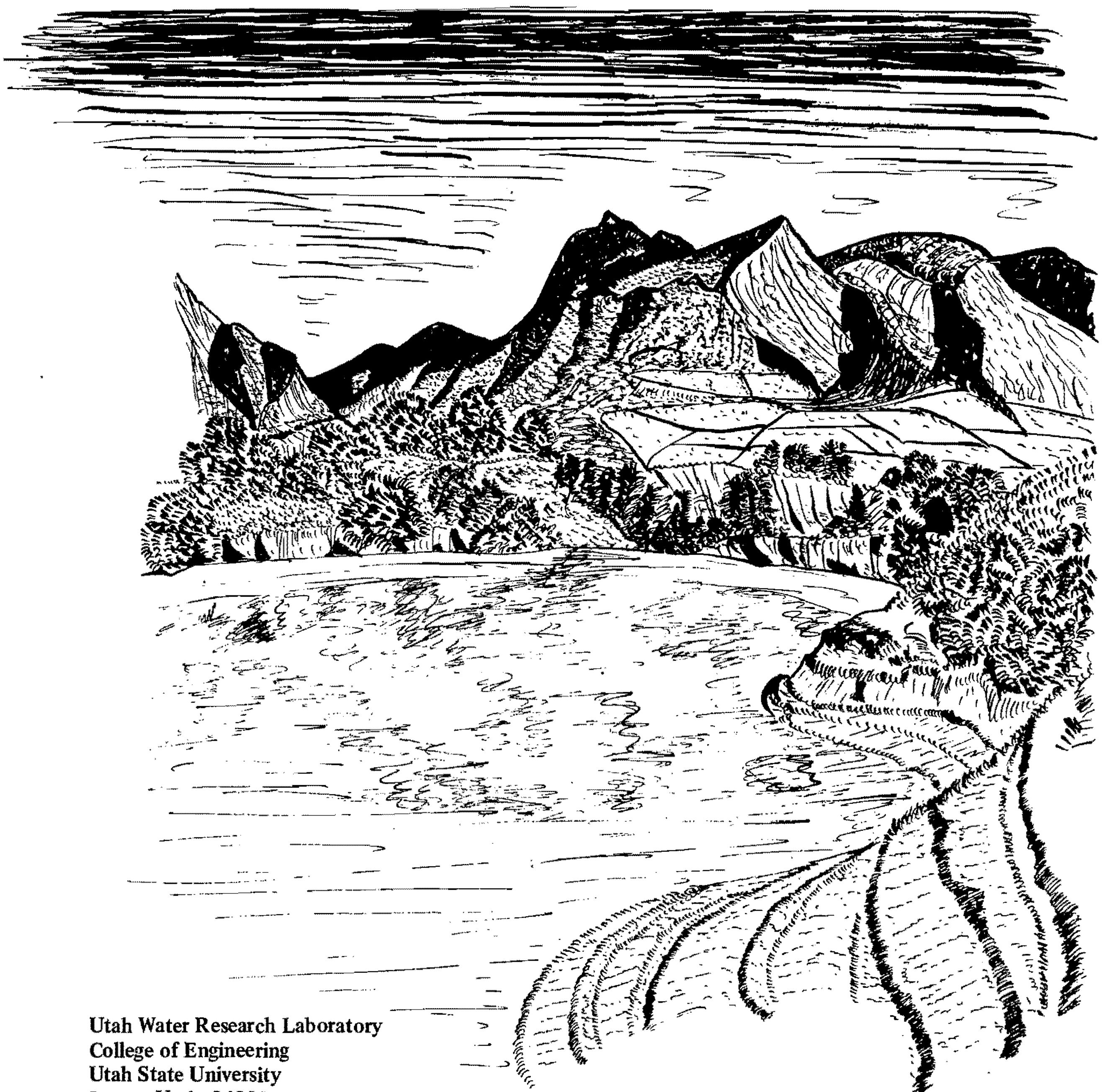

Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah 84322

December 1980

WATER RESOURCES PLANNING SERIES
UWRL/P-80/08

Summary Completion Report

VULNERABILITY OF WATER SUPPLY SYSTEMS TO DROUGHTS

by

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and
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ABSTRACT

This summary completion report describes the project work completed in three areas: 1) the development and preliminary testing of drought severity and vulnerability indices, 2) the impacts of Utah's 1977 drought, and 3) an operation comparison of stochastic streamflow models. The drought indices were evaluated for three municipal and three irrigation water supply systems in Utah. It was concluded that a continuous loss function to define the effects of water shortage would be more appropriate than the existing assumption that drought-related losses occur suddenly at a certain degree of water shortage. Information on the impacts of Utah's 1977 drought was collected by surveys of municipal and rural domestic systems, water users in Salt Lake County, and farmers, stockmen, ranchers, and irrigation company officials. Survey results were used to examine drought effects in different regions of the state and with respect to size of municipal supply systems. Despite severe restrictions placed on Salt Lake County water users most did not consider the experience an "undue burden." The comparison of five stochastic streamflow models on four Utah streams lead to a preliminary model choice strategy which is based on the historical estimates of the lag-one autocorrelation and Hurst coefficients.

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CHAPTER 1

INTRODUCTION

Overview

During a drought such as that experienced in 1977 in the western states, a great deal of political pressure develops to restrict water use. Two facts are often overlooked by those promulgating water conservation measures. One is that the appropriate water conservation activity differs from one community to another because of differences in 1) how the supply is affected by drought, and 2) the downstream usability of return flows. In addition, the appropriate water conservation activity varies according to the ease and consequences of reducing the use. A drought index that encompasses these factors would be much more useful for water planning than are the present indices based largely on weather information. Such an index would provide sound information on the probability of a water shortage (drought vulnerability) and the probable degree of shortage (drought severity) for use in planning water conservation programs and water supply augmentation facilities.

Project work encompassed 1) development and preliminary testing of drought severity and vulnerability indices, 2) a survey of responses to, and impacts of, the 1977 drought on municipal water supply systems in Utah, 3) a similar survey of agricultural water users in Utah, 4) a case study of water supply management by the Salt Lake Water Conservancy District during the 1977 drought, and 5) a comparison of stochastic modeling techniques for improving estimates of the probability of water shortages. Items 2 through 4 were undertaken in order to collect experiences of the 1977 drought before they are forgotten and as a valuable data base for continued development and testing of the indices. Item 5 was completed because of inadequacies identified in the estimates of the probability of water shortages obtained under item 1.

This report is divided into three main chapters describing project work on the drought indices, impacts of Utah's 1977 drought, and the comparison of stochastic streamflow models. For a more detailed account of work on the drought indices, which is described in Chapter 2, the interested reader is referred to Jensen (1978) and Jensen and Ellis (1979). Hughes et al. (1978) describe the impact of the 1977 Utah drought on several economic sectors plus the extensive responses to the drought by all levels of government. It provides amplification of most of the material in Chapter 3. Further detail on the operational comparison of stochastic streamflow models, which is summarized in Chapter 4, may be found in James, Bowles, and Kottegoda

(1980). The remainder of this introductory chapter comprises a brief synopsis of these three main chapters.

Drought Indices

The main purpose of this part of the research was to develop relatively simple and practical methods for conveying reliable information about droughts to those responsible for water supply management and planning. Two specific drought indices were developed and tested. The first, a drought severity index, is a measure of the degree of water shortage for a particular water supply system during a particular drought and is defined as follows:

$$\text{Drought severity index, } S = \frac{D - F}{D} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1.1)$$

in which D = water delivered by the system during an otherwise comparable drought-free period; and F = amount of water actually supplied during a drought. The second, a drought vulnerability index, is the probability that the drought severity index will exceed a preselected value of S'.

Three Utah municipal systems (Milford, Monticello, and Orangeville) and three Utah irrigation systems (the Milford area, the Logan, Hyde Park, and Smithfield Canal, and the Oberto ditch near Helper) were selected for development and preliminary testing of the drought severity and vulnerability indices. Using the available records, the drought indices were calculated. As a result of the preliminary testing it was concluded that future use of the vulnerability index should be defined using a continuous loss function for estimating damages associated with different time patterns and degrees of water shortage rather than as the probability of a drought of sufficient severity, S_i, to cause long-term economic losses as was originally proposed. The former definition does not conform with experience which shows that long-term economic losses for a particular type of economic activity do not occur suddenly at a certain degree of water shortage.

Impacts of Utah's 1977 Drought

A statewide water use survey made jointly with the Utah League of Cities and Towns near the end of 1977 contained a section related specifically to the impact of the 1977 drought. Usable responses were obtained from 154 of the 450 municipal and rural domestic systems and those responding serve all but a tiny fraction of the population. The survey included drought related questions on 1) water rate increase (usually to provide an economic incentive to reduce use), 2) emergency funding to supplement water supply, and 3) restrictions on water use. The survey results, including breakdowns of impacts by multicounty service districts, climatic regions, population served by the system, and type of water source were published in Hughes et al. (1978).

The Salt Lake County Water Conservancy District (SLCWCD) developed an extensive public information and customer feedback effort during and following the 1977 drought. Information obtained from the questionnaires revealed that 1) despite severe restrictions on the hours (evening only) when watering was permitted and very large penalties for exceeding monthly water allotments ($10/1,000 gallons) only 10 percent of customers considered that they had experienced an "undue" burden, 2) about half agreed that future droughts should be handled the same way and even those that suggested modified allotment formulae accepted the restriction concept. This acceptance is very interesting in view of the fact that total retail usage was decreased by 35 percent in June, 37 percent in July, and 50 percent in August. It was concluded that 1) the restrictions were very effective in achieving water conservation during the drought, and 2) a management policy of promoting water conservation might be effectively used to reduce both operating and capital costs during normal water years.

To learn more about how agriculture was affected by the 1977 drought, a letter survey was sent in May 1978 to several thousand farmers throughout the State of Utah. Responses were obtained from over 250 farmers and ranchers with 242 being complete enough for use in statistical analysis. A third of the irrigated farms reported severe crop losses whereas approximately three fourths of the dry farmers experienced crop failure. Stockmen and ranchers received most immediate government assistance and consequently actual loss of animals due to lack of water was minimal. Almost one fourth of the respondents reported water rights problems.

Comparison of Stochastic Streamflow Models

Estimates of the reliability of a water supply are typically based on analysis of an historic record of streamflow. Although, future streamflows may repeat historic magnitude distributions they will not duplicate time patterns. Several computer techniques are available for generating synthetic streamflow sequences with statistical properties similar to the historic record. From these sequences, better estimates of the reliability of a water supply can be made. Project work in this area has concentrated on a comparison of these computer techniques to formulate a procedure for choosing among them for generating synthetic hydrologic sequences.

Five stochastic hydrology models (second-order autoregressive, autoregressive-moving average (ARMA), ARMA-Markov, fast fractional Gaussian noise, and broken line) were calibrated to four Utah streams

(Bear River, Blacksmith Fork, Logan River, and Weber River) and used to generate synthetic streamflow sequences. These sequences were used to determine the reservoir capacities required to supply a hypothetical agricultural system with 98 percent reliability. The models were compared with respect to criteria including 1) their ability to preserve statistical measures of the short (lag-one autocorrelation coefficient) and long (Hurst coefficient) term persistence displayed by the historic streamflow records and 2) the economic regret associated with selection of a particular model. As a result of these comparisons a preliminary set of guidelines for model choice was proposed.

CHAPTER 2

EVALUATION OF DROUGHT SEVERITY AND VULNERABILITY INDICES

Introduction

During drought periods, a great deal of political pressure develops to restrict water use and to provide funds to augment existing water supplies. Also, water conservation practices vary widely among users. In dealing with the public and the press during emergency situations, differences in how water supplies are affected by drought and which water conservation practices are appropriate are often overlooked. Indices of drought that convey water supply and conservation needs would be more useful for the management of water supply systems and for planning purposes than are the present indices which are based largely on weather and climatic information. In the absence of objective information on needs, the selection of supply augmentation projects and conservation programs becomes too dependent on political influence. The measures that are implemented are less effective because of the lesser availability of information for planning purposes.

An important contribution to overcoming this difficulty is to make available to water supply managers and planners dependable information on drought conditions and drought effects on individual water supply systems. The probability of water shortage at the present time or in the immediate future (drought vulnerability) and the probable degree of shortage (drought severity) provides much of this needed information.

The overall objective of this part of the project work was to develop relatively simple and practical indices for improving the availability and reliability of information about droughts to those responsible for water supply management and planning. This information would improve the objective basis for the selection of effective water conservation measures during periods of "drought." The indices would be useful to planners in identifying priorities among proposed water supply developments from the consideration of water supply adequacy and vulnerability.

To provide the needed information content, two indices were developed: 1) a drought severity index for describing the state of a drought as it affects the availability of water for beneficial use in the past, the present, or the future; and 2) a drought vulnerability index for indicating the probability of water economic losses from shortage in a water supply system. The severity index describes the situation at a point in time and the vulnerability index represents long term exposure to drought losses. The research described herein includes the conceptualization and preliminary testing of drought severity and vulnerability indices. Testing was accomplished using data collected from three small municipal water supply systems and three irrigation systems in Utah.

Proposed drought severity indices for all six study systems were calculated and fitted to eight probability distributions, and a chi-square test was used to determine which distribution has the "best" fit. This distribution was then used to determine the probability that the drought severity index will exceed a certain value and these probabilities were used to define the vulnerability of each water supply system to drought. The drought indices were verified from data for general drought periods as defined by the Palmer Drought Index and public opinion as found in historical newspaper articles. In order to develop the drought vulnerability indices for planning purposes, a Box-Jenkins time series model of monthly Logan River streamflows was constructed; and 200 years of monthly synthetic streamflow were generated. Canal diversions were calculated from the synthetic streamflow sequence based on water diversion rights, and the drought severity and vulnerability indices were calculated.

Study Systems

The drought indices were tested using data collected from three municipalities and three irrigation areas, each having a different type of water supply source. The municipalities include:

1. Milford City, Utah, whose water is supplied by groundwater pumping.

2. Monticello City, Utah, whose water is supplied from springs.

3. Orangeville City, Utah, which depends upon surface streamflow from Cottonwood Creek.

The irrigation areas include:

1. The Logan irrigation area, which is located in Northern Utah, depends upon the Logan River for irrigation water. No storage facilities are available.

2. The Milford irrigation area, located near Milford, Utah, depends only upon groundwater pumpage for irrigation purposes.

3. The Oberto ditch irrigation area, located near Helper, Utah, obtains irrigation water from the Price River and has provision for storage in the Scofield Reservoir.

Drought Indices

Two indices are developed to assess the severity of drought and the vulnerability of a water supply system to drought. Definitions for the two indices are presented and discussed below:

1) Drought severity index,

$$S = \frac{U}{D} = \frac{D - F}{D} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.1)$$

$$= 1 - \frac{F}{D} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.2)$$

in which

S = drought severity index

D = total water demand, may be municipal demand (D_m) or irrigation demand (D_i)

F = furnished water demand, or the amount of water actually supplied to users

U = unfurnished demand, or the demand for water that is not filled because of drought related problems. It is also defined as the total demand (D) less the furnished demand (F)

2) Drought vulnerability index, V(S') is the probability that the drought severity index (S) will exceed a critical value, S', and can be written:

$$V(S') = Pr\ (S > S') \qquad (2.3)$$

The critical value S' should represent the drought severity at which significant economic losses will be experienced. Obtaining V(S') from a sequence of S values involves fitting the sequence with a probabilities distribution.

Drought severity index

The drought severity index (S) is structured so that increasing positive values of the index indicate increasing drought severity.

When the furnished demand (F) is equal to the demand (D), the drought severity index (S) is equal to zero, representing an adequate water supply. As furnished demand (F) decreases, the ratio of furnished demand (F) to demand (D) also decreases and the drought severity index (S) ranges from zero to one. Positive values of S imply a water shortage or drought for the water supply system. When the furnished demand (F) is greater than demand (D), the values of the drought severity index (S) are negative. Negative values of S represent periods in which there is a water supply surplus.

The numerator and denominator in the definition of the drought severity index (Equation 2.1) vary over time. Therefore, S is also a function of time. The demand referred to in Equation 2.1 is the usual or forecast level of water demand and does not reflect any reduction in demand due to conservation or regulatory measures implemented during a drought. These reductions are reflected in the quantity of the unfurnished demand in the numerator of Equation 2.1. A "current" severity index (S_c) can be calculated to indicate the present status of a drought by using the present values for the unfurnished demand and the demand. Alternatively severity indices (S_p) can be calculated for short or long-term planning using forecast or projected values of demand and supply over any defined period of interest. For planning purposes, the unfurnished demand depends upon the assumed drought conditions and operating policies for the water supply facilities.

Total demand (D) in Equation 2.1 is defined differently for municipal and irrigation systems. In both cases it is necessary that the definition remains consistent so that the resulting drought severity and vulnerability indices are comparable from location to location. With the following definitions of F, D_m and D_i, the indices are comparable.

Furnished demand (F). Furnished demand is defined as the amount of water actually diverted for use by a municipality or irrigation area. The definitions, methods of calculation, and data sources are summarized in Table 2.1. Historically furnished demand (F) is the measured diversion. For predictive or planning purposes, the furnished demand (F_f) is the forecast diversion.

Municipal demand (D_m). For municipalities, a demand definition is required that considers metered and unmetered systems, price of water, outside water use and population. Accounting for these factors makes possible comparisons between different municipalities. Differences in outdoor use of municipal water in different climatic divisions should also be considered if the comparisons are to be made between different climatic divisions. However, this was not necessary in this study. For metered systems demand can be obtained from meter records. For unmetered systems this is accomplished using the following water demand function developed for Utah by Hughes et al. (1978):

Table 2.1. Summary of furnished demand (F) definitions, calculations and data for case study areas.

Pilot Study	Definition of Furnished Demand (F)	Method of Calculation of Furnished Demand (F) (Raw Data & Calculation Results Appear in Appendix)	**Data Sources and Summary**
Milford City	Total amount of water, in gallons, pumped from three city wells during a monthly period.	End-of-month well meter total readings in gallons are algebraically subtracted from the previous month's readings for each of the three wells. The resulting volume for the three wells are added together to obtain total city well pumpage for each month of record.	(Richards, 1977) monthly meter readings August 1967 through June 1977
Monticello City	Total amount of water diverted from spring and streamflow and treated for culinary use	Total monthly Monticello City treatment plant influence in million gallons as reported by King, et al. (1976)	(King, et al., 1976) monthly data January, 1966 through August, 1977
Orangeville City	Total amount of water diverted from streamflow and treated for culinary use	End-of-month city treatment plant influent meter readings are subtracted algebraically from the previous month's meter reading.	(Orangeville City 1977) daily meter readings November 1969 through June 1977
Milford Irrigation Area	Total amount of water reported as pumped for irrigation use in the Milford, Utah irrigation area.	Total area well pumpage data abstracted from the Water Commissioner's Report (Strong, 1977) and the State Engineers Office, State of Utah (1977).	(Strong, 1977 and State Engineers Office, State of Utah, 1977) Seasonal well pumpage 1958 through 1977
Oberto Ditch (Helper) Irrigation Area	Total seasonal canal diversions from the Price River, including flows from storage in Schofield Reservoir	Total seasonal diversion from the Price River including storage, as recorded by the Price River Commissioner and reported by the State Engineers Office.	(State Engineers Office, State of Utah, 1977) Seasonal diversions from Price River 1942 to 1976
Logan Irrigation Area	Total monthly diversions to the Logan, Hyde Park, and Smithfield Canal from the Logan River.	Total monthly diversions as measured at the Logan, Hyde Park, and Smithfield Canal head and published by the U.S. Geological Survey.	(U.S. Geological Survey, 1901-1977) daily and monthly records for water years 1901 to 1977.
Planning Study Logan Irrigation Area	Projected monthly diversions to the Logan, Hyde Park and Smithfield Canal from synthetic stream flow records produced for the Logan River.	Synthetic diversion data is generated by a sophisticated time series auto-regressive moving average model developed in this study for the Logan River and diversions to the Logan, Hyde Park and Smithfield Canal.	(U.S. Geological Survey 1901-1977) Synthetic monthly data generated for 200 years or 2400 months.

$$D_{md} = 40.75 + 30.54 \ln \frac{1}{P} + 24.14(I) \quad . . . . (2.4)$$

in which

D_{md} = average demand of water per person per day

P = average cost in dollars per thousand gallons

I = outside use index described below

Outside use is considered because of the great variation of this component among the Utah systems. Hughes et al. (1978) developed an index which assigns an integer from 1 to 9 to a system according to the outside uses served (see Table 2.2).

Equation 2.4 provides a reasonably accurate and consistent method of calculating water demands. The monthly municipal demand (D_m) is calculated from the municipal daily demand (D_{md}) as follows:

$$D_m = D_{md} \, d \, M_w \, P_0 \quad . . . . (2.5)$$

where

d = number of days in a year (i.e. 365)

M_w = fraction of annual per capita use which occurs in the month of interest, estimated from available water use records in Utah.

P_0 = population estimate, number of people

Irrigation demand (D_i) is defined as water that is diverted for farm irrigation purposes. This demand includes transmission losses of the system, system losses, and plant consumptive use. Consumptive use is defined as the amount of water transpired in the process of plant growth plus the water evaporated from soil and foliage in the area of the growing plants. In this study consumptive use was estimated using the Soil Conservation Service modification of the Blaney-Criddle method (U. S. Department of Agriculture 1967) with monthly crop coefficients tabulated by Ogrosky and Mockus (1964). The monthly irrigation demand (D_i) then is simply calculated as the consumptive use multiplied by the irrigated area and divided by the irrigation efficiency estimated by Griffin (1978).

Drought vulnerability index

The drought vulnerability index, V(S'), is defined as the probability that the drought severity index will exceed a critical value,

Table 2.2. Outdoor use index, I (after Hughes et al. 1978).

I	Extent of outdoor use from municipal water
1.	No outdoor use from domestic system--everyone has connection to pressurized dual system.
2.	Almost no irrigation from domestic system--supplementary system is available which serves at least 85 percent of outside demand.
3.	Supplementary ditch system is available and landscaped areas are very small.
4.	No supplementary system is available but landscaped areas are very small.
5.	Ditch system available for gardens but most lawns are irrigated from domestic system.
6.	Ditch or piped system available to some customers but most outside irrigation is from domestic system.
7.	All outside demand from domestic system--moderate amount of landscaping, average climate.
8.	Large amount of landscaping and all from domestic system--average climate.
9.	Large amount of landscaping and all from domestic system--hot and dry climate.

S'. For this study, the critical value (S') is assigned as zero, or the value at which furnished demand (F) is equal to total demand (D) (see Equation 2.2). Values above zero represent a water shortage or drought. The probability of exceeding the critical value of zero, is considered to be the probability of drought occurrence. Critical values can be set for any level of drought severity and their probabilities calculated. For example, S' may be set at a value corresponding to a critical furnished demand below which severe economic losses may be incurred by the water user.

Generation of Synthetic Drought Indices

To demonstrate the use of the drought indices for planning purposes the Logan irrigation area was chosen as a case study. The generation of the drought indices was accomplished by generating synthetic irrigation diversion data for furnished demand and by generating synthetic mean temperatures for use in Blaney-Criddle calculation of the demand function. The Logan study area receives its irrigation water from the Logan, Hyde Park and Smithfield canal which diverts water from the Logan River. Monthly synthetic streamflows for the Logan River were generated and then monthly synthetic canal diversions were derived from the streamflows using a water rights diversion rule. The synthetic streamflows for the Logan River were generated using a univariate ARMA model (autoregressive moving average). Following the Box-Jenkins model identification, parameter estimation, and diagnostic checking procedure led to the following multiplicative ARMA (1,0)(0,1) seasonal model being selected:

$$Z_t = 0.63157\ (Z_{t-1} - Z_{t-13}) + Z_{t-12} + 0.80365\ a_{t-12} + a_t \quad .(2.6)$$

in which

Z_t = streamflow volume in month t

a_t = error term in month t

t = month index

With the model in this form, synthetic streamflow values (Z_t) can be readily generated. Of the 220 years of generated record, the first 20 years were discarded to remove any bias resulting from initial conditions leaving 2400 months of synthetic data. Using only those months in the irrigation season, the synthetic canal diversions were calculated and used as the furnished demand (F).

In order to calculate the irrigation demand function the mean monthly temperature is necessary. To provide an estimate for these values, a normal, independent random number was used to estimate the mean monthly temperature and hence estimate irrigation demand and the drought severity index. The drought severity and vulnerability indices were then calculated by the usual procedure.

Selection of a Probability Distribution for Drought Severity

In choosing the probability distribution of the drought severity index the calculated severity indices for each of the study systems were fitted to the following probability distributions using computer programs written by Schmidt (1975) and McKee (1978): normal, Pearson Type III, Gumbel, Rayleigh, Gamma, Beta, log-normal and log-Pearson Type III. The chi-square goodness-of-fit test indicated that the lognormal distribution provided the "best fit" for all study system areas and that distribution was therefore used to calculate the drought vulnerability index.

Municipal System Results

For the period of record of each of the three study systems, the drought severity index was calculated monthly. As an example, Figure 2.1 contains plots of the monthly values of the severity index for Monticello City at four alternative water prices. The upper line is for the lowest price of $0.20 per 1,000 gallons and the lines in decreasing order of magnitude of the severity index are for the $0.50, $1.00, and $2.00 per 1,000 gallons prices. Thus higher prices decrease the municipal demand and hence decrease the severity index. There is no consistent seasonal pattern in the severity index except that values are usually low, indicating no shortage, during the spring snowmelt season. Monticello derives its supply from springs; and as the severity index indicates, it is continually in a water short situation by late summer.

Table 2.3 compares, for the three municipal systems, the number of months for the years 1970-1977 in which the drought severity index exceeds the critical zero value. It also contains a comparison of the annual drought severity sums obtained by summing values of the drought severity index for each month in which it is positive. These results indicate that Monticello usually has both the largest number of drought occurrences and the largest annual severity sum. Orangeville depends exclusively on a surface streamflow supply, but its supply is relatively less utilized than Monticello's, and therefore it has suffered less from drought historically. Milford, which derives its water supply from groundwater, has been much less prone to drought than either Monticello or Orangeville.

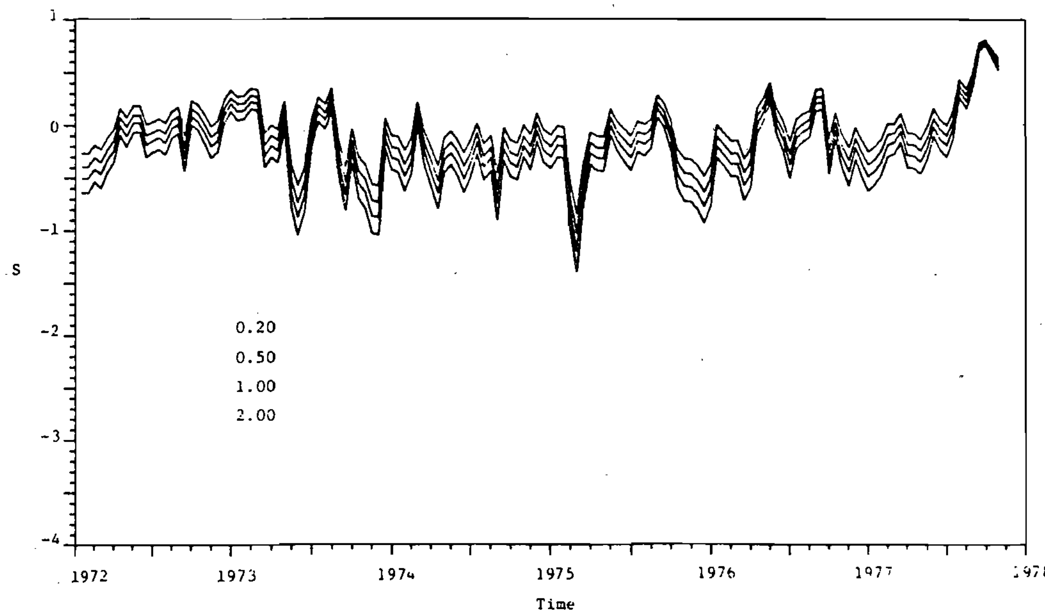

Figure 2.1. Drought severity index for Monticello City at four alternative water prices.

Table 2.3. Comparison of number of drought occurrences and annual drought severity sums, for municipal study systems (water price is $0.20 per 1,000 gallons).

	Number of Drought Occurrences			Annual Drought Severity Sum		
Year	Milford	Monti-cello	Orange-ville	Milford	Monti-cello	Orange-ville
1970	1	1	1	.04	.21	.16
1971	1	2	0	.20	.12	0
1972	1	2	6	.19	.18	.96
1973	4	5	6	.55	.59	.38
1974	0	5	3	0	1.02	.27
1975	1	5	5	.01	.96	1.09
1976	0	5	6	0	.31	1.07
1977*	2*	6*	4*	.09*	2.98*	.92*

*For the period January-June only

The drought vulnerability index for each community is presented in Table 2.4 for the four prices of water. As recognized in the prior discussion of the severity indices, the municipalities ranked in order of decreasing drought vulnerability are: Monticello, Orangeville, and Milford. This ranking is the expected order based on the usual notion of drought susceptibility of the types of water supply which are spring, surface streamflow, and groundwater pumping, respectively, and corroborated by the municipal water use survey reported in Chapter 3.

The sensitivity of the municipal drought vulnerability to the price of water is shown graphically in Figure 2.2 as a percentage reduction in vulnerability with increasing price. Price enters the calculation of municipal demand through the demand function (see Equation 2.4). Over the range of prices examined the municipalities, ranked in order of increasing sensitivity of vulnerability to price, are: Monticello, Milford, and Orangeville. In other words by increasing the price by a factor of 10 Orangeville can reduce its

Table 2.4. Drought vulnerability index for the municipal systems at alternative water prices.

City	Price of Water (dollars/thousand gallons) $0.20	$0.50	$1.00	$2.00
Milford	15.5	10.4	7.5	5.4
Monticello	45.9	32.7	24.1	16.8
Orangeville	34.9	19.6	11.5	6.3

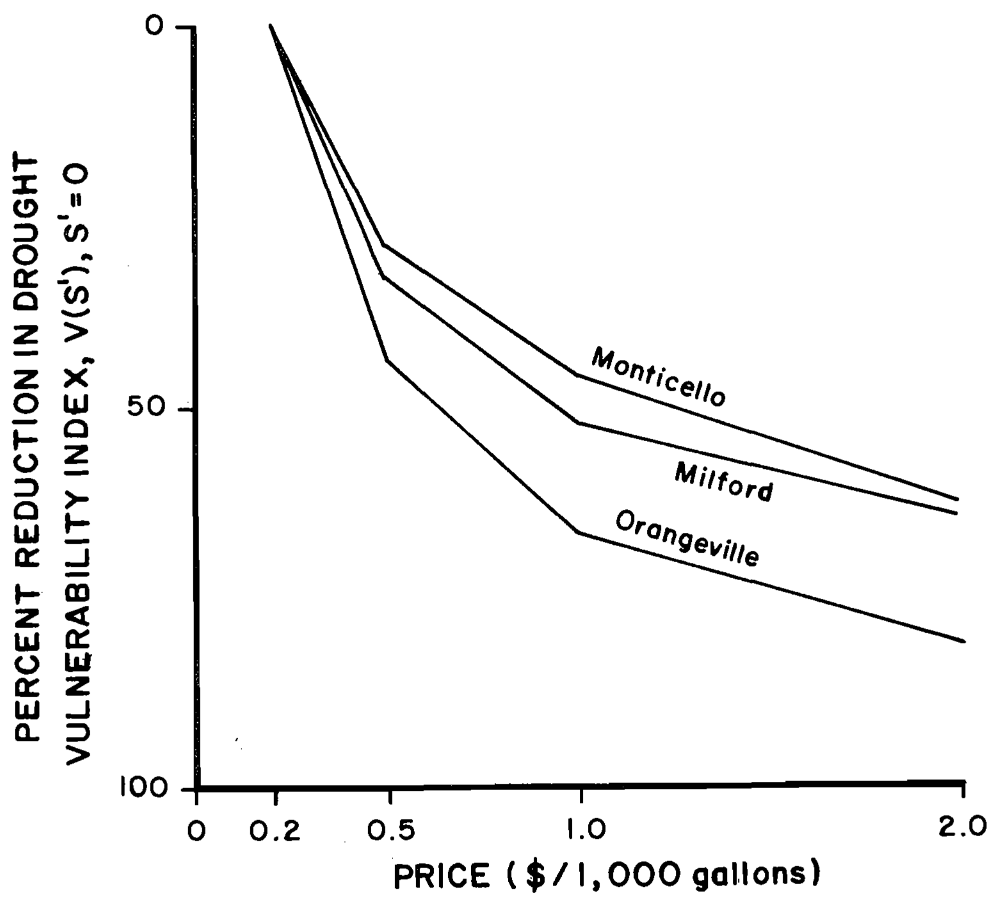

Figure 2.2. Sensitivity of municipal drought vulnerability to price of water.

vulnerability by 82 percent, to a probability of only 6.3 percent, whereas Monticello's reduction for the same price increase is only 63 percent, to a probability of 16.8 percent. Obviously this kind of information is potentially very useful to a water supply planner or decision maker. Calculations could also be made to show the effect of capacity expansion on both the severity and vulnerability indices.

In an attempt to evaluate the usefulness of the drought severity index, it was compared with the Palmer drought index (Magnuson 1969, Palmer 1965, and Richardson 1977). The drought severity index is applicable to drought conditions faced by a specified water supply system whereas the Palmer drought index is a regional meteorological index for both wet and dry periods which was orginally developed for use in the agricultural areas of the midwestern United States. Also the Palmer index is based on precipitation and soil moisture considerations and does not reflect the effects of drought on groundwater and thus streamflows derived from subsurface sources. Hence, the two indices are not expected to agree exactly, but during years of extreme drought both indices should indicate drought, at least in streamflow-supplied systems. As an additional check, drought consequences as they affect public concern about water generally, were measured for this study by counting the number of related articles that appeared in a regional daily newspaper for the 1958-1976 period. Again, while not being a direct index of drought consequences, the frequency of articles appearing in the newspaper can be expected to be an indicator of drought severity. Neither of these indices would be expected to follow the same time pattern as the drought severity index, but their patterns would be expected to exhibit similarities.

The best agreement between the drought severity and Palmer indices was obtained for the streamflow-supplied city of Orangeville. The number of monthly drought occurrences indicated by a positive drought severity index at $0.20 per 1,000 gallons and a moderate to extreme monthly Palmer drought index (i.e. more negative than -2.00) at Orangeville are tabulated for several years in Table 2.5. Also tabulated for comparison are the number of drought related newspaper articles in each year. There is good agreement between the two drought indices for all years except 1975 in which the Palmer index indicated only mild drought conditions in six months (0 to -1.99). The number of newspaper articles appears to log both severity indices.

Irrigation System Results

A cross-sectional comparison of the drought severity indices for the three irrigation systems for the period 1958 through 1977 is found in Table 2.6. Each area experienced drought, but the Milford area is affected much more severely than the other two areas, and in fact is continuously in a water short situation. However, the 1977 drought

Table 2.5. Comparisons of drought indices for Orangeville, Utah.

Year	Number of Drought Occurrences		Number of Newspaper Articles
	Drought Severity Index ($0.20 per 1,000 gallons)	Moderate Palmer Drought Index	
1970	1	0	0
1971	0	2	0
1972	6	6	0
1973	6	4	5
1974	3	3	9
1975	5	0	7
1976	6	2	3
1977	4*	6*	**

*Only January through June considered
**Not available

conditions affected the Logan area, which is dependent upon natural streamflow, more severely than the Milford area which derives its supply from groundwater pumping and where installed well capacity is known to be inadequate in normal years.

The drought severity index calculated for the May through September irrigation season at Logan is listed in Table 2.7. Also listed for comparison are the number of occurrences of a moderate to extreme (i.e. greater than -2.0) monthly Palmer drought index for the Northern Mountains Region, and the number of newspaper articles related to agricultural drought. Since the Palmer index was calculated for each month of the irrigation season, the maximum number of moderate drought occurrences is five. In all years in which the drought severity index was positive (i.e. 1931, 1934, 1961, and 1977), the Palmer index indicated several moderate drought months. In other years in which up to five moderate drought months were indicated by the Palmer index the meteorologic and drought conditions on which the Palmer index is based apparently did not reduce the streamflow enough to adversely affect the Logan irrigation system. There is apparently little correlation between the number of newspaper articles and the drought severity index. However, Jensen (1978) has found that weak nonparametric tests based on accumulated totals do indicate significant correlations between these two variables for all systems.

Table 2.6. Comparison of drought severity index among irrigation systems.

	Drought Severity Index Values		
Year	Logan Area	Milford Area	Helper Area
1958	-.49	.17	.59
1959	-.52	.28	.51
1960	-.31	.22	.41
1961	.03	.29	.46
1962	-.27	.22	.01
1963	-.15	.29	.56
1964	-.21	.20	.17
1965	-.68	.16	.08
1966	-.29	.20	.15
1967	-.29	.22	-.02
1968	-.46	.18	-.08
1969	-.36	.22	.15
1970	-.23	.08	.09
1971	-.17	.05	-.10
1972	-.74	.11	.14
1973	-.46	.15	-.29
1974	-.80	.02	-.04
1975	-.72	.00	-.29
1976	-.50	.07	.32
1977	.33	.20	*

*1977 data not available

Table 2.7. Comparison of drought indices, for the Logan, Utah irrigation area.

Year	Seasonal Drought Severity Index	Number of Occurrences of Moderate Monthly Palmer Drought Index (Northern Mountains Region)	Number of News-Paper Articles (Agriculture)*
1931	.12	5	
1932	-1.08	4	
1933	- .53	5	
1934	.36	5	
1935	- .41	5	
1936	- .82	0	
1937	- .56	0	
1938	- .63	0	
1939	- .35	0	
1940	- .13	4	
1941	- .11	0	
1942	- .17	0	
1943	- .82	0	
1944	- .05	0	
1945	- .80	0	
1946	- .95	0	
1947	- .54	0	
1948	- .72	0	
1949	- .68	0	
1950	- .97	0	
1951	- .84	0	
1952	- .80	0	
1953	- .52	0	
1954	- .39	0	
1955	- .33	0	
1956	- .50	0	
1957	- .41	0	
1958	- .49	2	2
1959	- .52	0	10
1960	- .31	4	8
1961	.03	3	9
1962	- .27	0	1
1963	- .15	2	5
1964	- .21	0	4
1965	- .68	0	0

Table 2.7. Continued.

Year	Seasonal Drought Severity Index	Number of Occurrences of Moderate Monthly Palmer Drought Index (Northern Mountains Region)	Number of News-Paper Articles (Agriculture)*
1966	- .29	0	7
1967	- .29	0	0
1968	- .46	0	0
1969	- .36	0	2
1970	- .23	0	0
1971	- .17	0	1
1972	- .74	0	12
1973	- .46	0	0
1974	- .80	2	14
1975	- .72	0	0
1976	- .50	0	1
1977	.33	5	

*Not available 1931-1957, 1977

Table 2.8 contains the drought vulnerability indices for the three study irrigation systems. A comparison of these vulnerability indices calculated for the irrigation season and based on historical data, again shows that Milford is the most vulnerable to drought and Logan the least vulnerable. The furnished demand at Milford is estimated by the installed well capacity and therefore any increase in this capacity would directly reduce its vulnerability. The vulnerability at Logan, calculated on a monthly basis, is higher than the seasonal vulnerability because water shortages in later months are not compensated for by surpluses in earlier months. A similar result would be expected for all systems and the monthly vulnerability index should never be less than the seasonal vulnerability index. It is disturbing to note that the vulnerability indices for Logan based on the synthetic data are much lower than those based on the historical data indicating that the synthetic events were less severe than the historic. However, further data generation studies with alternative stochastic model structures resulted in synthetic data sequences which contained more severe events than the historical events. This work is reported in Chapter 4.

Table 2.8. Comparison of irrigation system drought vulnerabilities.

System	Data Base	Irrigation Season	Monthly
Logan	Historical	8.56	22.2
	Synthetic	0.0003	4.9
Milford	Historical	97.7	-*
Oberto Ditch	Historical	44.5	-*

*Not calculated.

Conclusions and Potential Applications of Drought Indices

The drought indices can be applied to past, current or future drought conditions for the following purposes: 1) drought forecasting, 2) cross-section comparison of drought severity among water supply systems, 3) management of available water supply during drought, 4) planning water supply augmentation to alleviate drought conditions, and 5) planning new water supply systems to function effectively during droughts.

In order to compare the effect of a drought affecting many communities the drought severity and vulnerability indices for each municipality must be derived using the same demand function and commensurate furnished demand information. For example, the comparison might be used in order to make a recommendation on which communities should receive loans to increase water supply capacity. Additional information, such as the expected growth rate of a community or the effects of adding additional water supply capacity to any of the communities can also be incorporated for planning purposes.

Local water supply managers and planners can calculate the drought severity and drought vulnerability indices on any time basis (e.g. weekly, monthly) suited to their needs. Calculation of the drought severity index (Equation 2.2) is not difficult and can be performed and updated by anyone with a small amount of training.

The drought indices can enhance the management of a local water supply by providing information on:

1. When a drought begins and ends based on the duration of positive drought severity indices.

2. What the probability is that drought conditions will affect a water supply.

3. What level of effort or degree of restriction should be put into adjustments to drought (price restrictions, reuse, rotation, weather modification, emergency supplies) as estimated from the effect of various efforts on the severity index.

4. What timing is appropriate for beginning or ending special drought adjustment efforts as estimated from when they significantly reduce the severity index or take a community out of a drought situation.

5. When to increase the water supply capacity or when to seek funding for new supplies based on population growth or increased use projections

For example, during 1977 the City of Monticello decided to drill four wells to double its water supply capacity. An alternative to increasing the installed well capacity would have been to reduce the demand through increasing the price. The drought vulnerability information calculated in this study, though not available for the Monticello City planners, indicated that the probability of water shortage in the immediate future is 46 percent when water is priced at $0.20 per 1,000 gallons. Were the price raised to $2.00 per 1,000 gallons the probability is 17 percent. If a certain risk of water shortage is unacceptable, say 15 percent, then the City of Monticello should not try to "price" themselves out of drought conditions but rather to increase their water supply capacity in an increment at least large enough to decrease the probability of water shortage to an acceptable level at an acceptable price.

Another example is the City of Orangeville. The managers of that city have decided to increase the size of their culinary water treatment plant to decrease the likelihood of drought conditions. The drought vulnerability for Orangeville at $0.20 per 1,000 gallons is 35 percent. Were the price raised to $2.00 per 1,000 gallons, the probability of water shortage would decrease to 6 percent. In this case perhaps a viable alternative would be to increase water prices to at least $1.00 per 1,000 gallons at which the probability of water shortage is 11 percent. The conclusion is that the increased drought information presents objective information for better evaluation of a wide range of alternatives for water supply planners and managers.

The critical value of the severity index used in this study to calculate the vulnerability index was zero. In selecting this value it was recognized that it implies from the definition of the vulnerability index that significant economic losses will be increased if there is any water shortage, however small. This is obviously unrealistic because much wastage and inefficiency in use can be readily eliminated at little cost (see Chapter 3). Therefore, it was concluded that the vulnerability index should be defined using a continuous loss function for damages associated with different degrees of water shortage rather than as the probability of a drought of sufficient severity to cause long-term economic losses as was originally proposed. The original definition does not conform with experience which shows that long-term economic losses for a particular type of economic activity do not occur suddenly at a certain degree of water shortage.

Recommendations for Further Study

1. Price should be included in the demand function for irrigation areas.

2. The annual municipal demand function adapted for use in this study should be developed at the monthly level. This should give better resolution to the drought indices.

3. Drought consequence data (e.g. reduction in agricultural yields, loss of landscaping) should be collected in the areas studied to better evaluate the calculated drought severities.

4. A study should be conducted in which synthetic water supply data are generated for a municipality in order to extend the indices to municipal water supply planning.

5. A function should be established to estimate economic losses (see Russell et al. 1970) so that the drought severity and vulnerability can be evaluated in terms commensurate with water supply augmentation alternatives. Perhaps a crop yield model could be used to evaluate the loss function for an irrigated area.

6. Several complex water supply systems should be studied to provide additional testing of the drought indices.

7. Drought forecasting and planning for drought in water supply systems should be considered in light of the drought severity and drought vulnerability indices. Drought forecasting can probably be done by forecasting the water supply (streamflow) and combining that forecast with population or temperature prognostications. These values could then be incorporated into the drought severity index.

8. A method should be established to educate water supply planners and managers on the methods of evaluating drought using the techniques developed in this study.

9. The technical and institutional problems in practical application of the drought indices to water management decision making during drought need to be identified and evaluated.

CHAPTER 3

IMPACT OF UTAH'S 1977 DROUGHT ON MUNICIPAL AND AGRICULTURAL WATER USE

Impact on Municipal Water Use

Introduction

The 1977 drought was felt in various ways in varying degrees by every municipal water utility in Utah and by the people they serve. This assessment is divided into two parts. The first summarizes effects on 154 municipal water utilities scattered over the state, and the second analyzes the impact on Utah's second largest water utility, the Salt Lake County Water Conservancy District (SLCWCD). The first part surveys the breadth of the drought impact, and the second part looks into what happened in sufficient depth to provide some understanding of the principal interactions among drought conditions, water utilities, and water users.

Data on what happened to communities throughout the state were compiled from a statewide water use survey made jointly by the Utah Water Research Laboratory and the Utah League of Cities and Towns near the end of 1977 (Hansen et al. 1979). Because of the fortuitous timing of this survey, a section related specifically to impact of the 1977 drought was added to the questionnaire. Usable responses were obtained from 154 of the 450 municipal and rural domestic systems to whom the questionnaire was sent. Since virtually all of those not responding were from very small rural systems and altogether they serve only a tiny fraction of the population the results provide excellent population coverage.

Data on what happened in the Salt Lake County Water Conservancy District were obtained by analysis of water use data kept routinely by the district and from a special survey the district made of its customers following the drought.

Statewide survey

Scope. The survey of municipal water utilities asked drought related questions on three basic factors: 1) Water rate increases during the drought (usually to provide an economic incentive to reduce use), 2) emergency funding to supplement water supply, and 3) restrictions on water use. The following discussion considers drought impacts by multicounty districts (Figure 3.1), climatic districts (Figure 3.2), population, size of system, and type of water source.

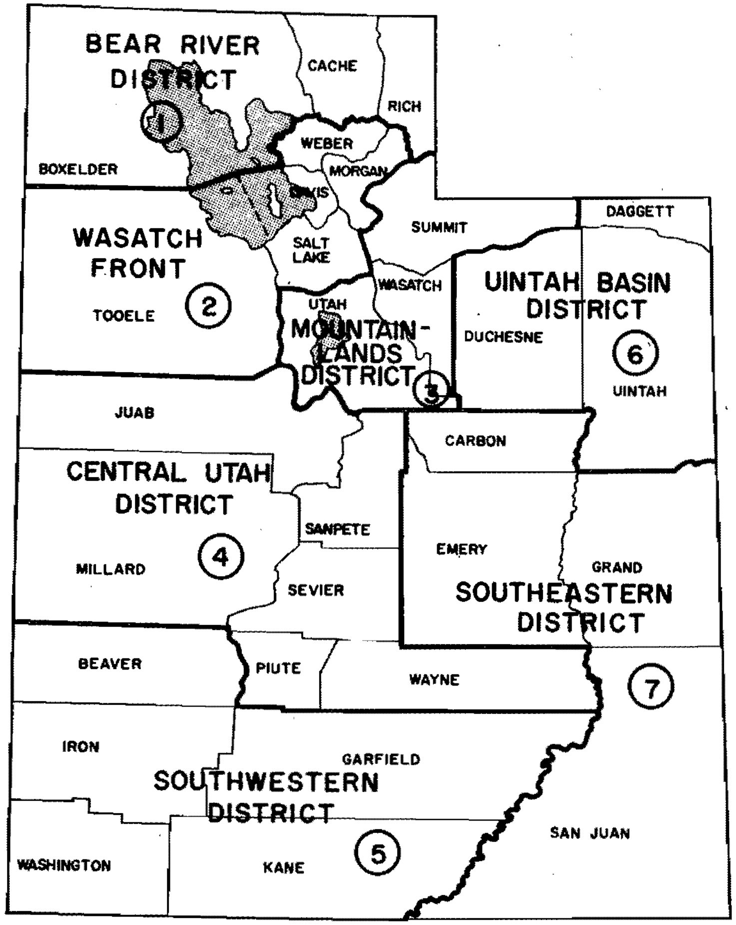

Figure 3.1. Location of Utah multicounty districts.

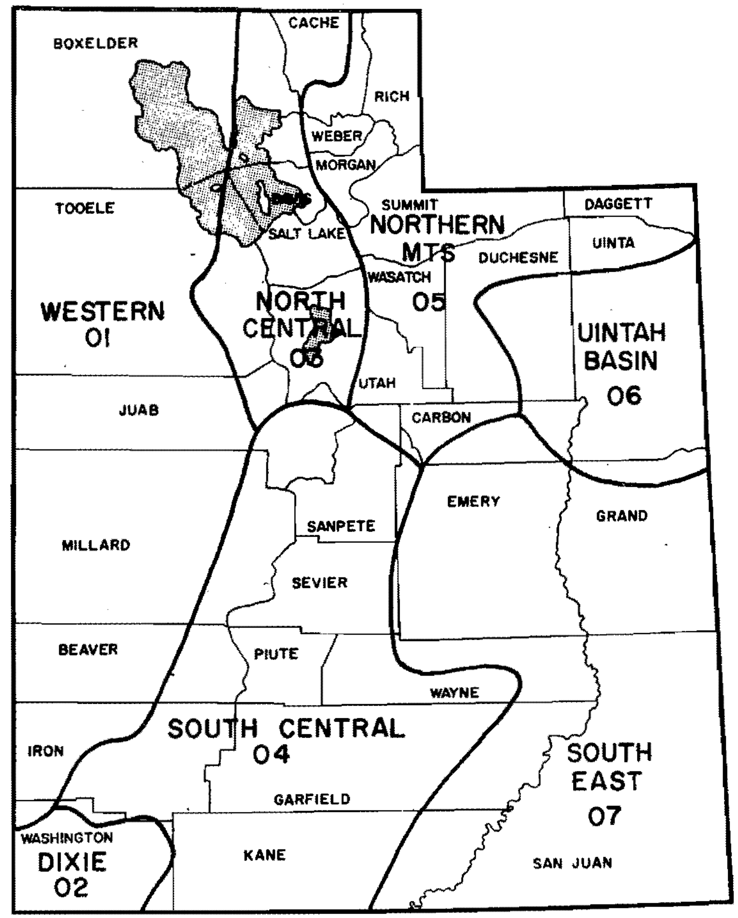

Figure 3.2. Location map for Utah's seven climatic divisions.

Water rate increases. Statewide, 36.4 percent of the systems increased the price charged for water during 1977. Only one-third of these admitted that the rate increases were caused by the drought; however, it is likely that this report was influenced by a reluctance on the part of many utilities to go back to the old rates after having gone through the painful process of justifying a rate increase to their customers. Only 30 percent of the systems which increased their rates indicated an intention to reduce charges when the drought ended.

Geographically, very few utilities increased water rates in the Mountain Lands district, which is usually an area of excess water, and in the Southwestern district, which is an area of perennial shortage where drought is the rule rather than the exception. About half of the systems along the Wasatch Front and 73 percent of Uintah Basin systems increased water charges.

There was no correlation between size of system and the number of systems which increased rates. There was, however, a strong correlation between types of water source and number of systems which increased their rates; namely, 73 percent of those which use surface water as that supply increased their rates while only 30 to 32 percent of those using spring and well sources did so.

Emergency funding. Statewide, 16 percent of the systems reporting received drought emergency funding during 1977. Geographically, there was no correlation with distribution of drought funds, perhaps indicating a political reluctance to favor one region over another; however, there was a very strong correlation with the size of the system. None of the systems serving more than 5000 people reported receiving emergency funds. This likely reflects both a state policy of limiting assistance to small communities, and the importance of economies of scale in cost of water supply systems and the ability of larger systems to solve their own financial problems.

Restrictions on water use. On a statewide basis half of the water systems restricted water use by their customers during the drought. Two thirds of these restrictions were initiated during the drought. One sixth of the systems in the state already had some form of restrictions. Of the systems with restrictions, half were mandatory and half were voluntary. Most restrictions were begun during May or June 1977 and ended in September or October at the close of the irrigation season. About 22 percent of the systems continued the restrictions, at least into 1978.

The most common form of restriction, accounting for about 44 percent of the total, was a limitation on both days of the week and hours of the day when individuals could sprinkle yards, 16 percent of the systems limited days only, and 11 percent limited hours of the day only. Six systems went so far as to allow no outdoor use. The people those systems serve suffered substantial loss of landscaping.

Geographically, restrictions were most common in the Southeastern district (80 percent of the systems) and also occurred extensively in the Uintah Basin (71 percent). The Wasatch Front experienced restrictions in 61 percent of the systems while other districts varied from 33 to 45 percent.

The use of restrictions was surprisingly correlated with population. Despite the extensive use of restrictions in the Southeast and Uintah Basin (areas with mostly small systems), the largest systems in the state were the most likely to restrict usage. Nine systems in Utah serve more than 25,000 people, and seven of these (78 percent) used restrictions. This compares with use limitations by less than 40 percent of the systems serving less than 2,500 population. The relationship can be at least partially explained by the fact that more of the larger systems use surface water sources, and these were most impacted by the drought. Specifically, 86 percent of those systems which use surface water for at least part of their supply, used restrictions. This compares with 46 percent of systems which use springs only and 39 percent of systems which rely exclusively on wells.

Impact on Salt Lake County Water Conservancy District

Background

The SLCWCD is both a water wholesaler and retailer to rapidly growing areas of Salt Lake County. This district serves approximately 6,600 retail customers in neighborhoods ranging from single family residential to a mixture of commercial establishments and multiple dwelling units. This utility was selected for detailed discussion, not because it was more severely impacted by the drought than other utilities, but rather because 1) it conducted a very extensive campaign to communicate information on the drought to its customers including justification for its mandatory restrictions; and 2) it obtained excellent feedback on drought experiences from a large fraction of its retail customers during the following winter.

Communication with retail customers

In a planned program to communicate with its customers, the utility responded to telephone inquiries, granted interviews, and prepared media releases. However, the principal drought-related communication was a planned series of written messages mailed with each water bill. These messages are summarized as follows:

February/March 1977. A rather lengthy bill stuffer stressed the apparent implications of the lowest snowpack on record, requested voluntary conservation wherever possible, and described ways to conserve in the home.

April 1977. The normal two-month billing period was reduced to monthly, and rules for voluntary water restrictions were put into effect. The goal of the voluntary program was to cut outdoor use by 50 percent. The rules were: 1) Outside watering limited to only 4 hours per week; 2) limit outside use to the hours of 8 pm to 10 am; 3) even numbered houses water on Monday, Wednesday, and Friday; odd numbered houses water on Tuesday, Thursday, and Saturday; and no watering on Sunday.

May 1977. A $10 per 1,000 gallon penality was implemented for water use over an allotted amount. The monthly allotments were determined from average meter readings in each neighborhood and were the same for each customer in the neighborhood. They were computed as average 1976 indoor use plus 50 percent of 1976 outdoor use for each neighborhood. Neighborhood figures varied widely from 14,000 to 41,000 gallons. This $10 penalty compared to 25 cents as the normal unit cost of water.

June 1977. The message thanked the customers for almost universal cooperation with the conservation program, reviewed the restriction rules, and answered many telephone questions.

July 1977. The message informed customers of continuing drought conditions and described how a customer could allocate his water better within his restrictions by reading his meter frequently.

August 1977. Restrictions were relaxed by allowing a 50 percent increase in use without penalty and Sunday watering was allowed.

September/October 1977. All restrictions on days and hours were terminated, but voluntary conservation was still encouraged.

November/December 1977. New drought information and a questionnaire including a series of questions on the drought experience were mailed to each retail customer.

January/February 1978. A summary of the survey results was mailed to each customer.

Results of the survey

The November/December questionnaire was answered and returned by 2,500 of the approximate 6,600 customers. Many of the yes/no questions also invited individual comments on inequities and suggestions on how the restrictions could have been better handled. The wide variety of responses make fascinating reading but will be discussed here only to the extent that they can be categorized into significant group opinions. The following is a summary of the questions and responses:

1. Do you feel that our water restrictions imposed an undue burden rather than an inconvenience on your household?

   10% said Yes, 84% No, 6% No response

2. If we must use water restrictions again in the coming year to control water use, what basis would you like to see us use to determine the amount of water you could use?

   48% said Same as Last Year, 35% Based on Size of Family, 35% Based on Size of Yard, 5% each Household an Equal Amount, and 7% offered some other plan. A number of people indicated more than one choice on this question.

3. Do you feel that our $10 per 1,000 gallon surcharge on excessive water use was a reasonable and fair way to make water users aware of the need to conserve water?

   70% Yes, 22% No, 8% No response

4. Do you feel that it is reasonable for us to ask you to water before 10 am and after 8 pm and on every other day during the summer?

   72% Yes, 25% No, 3% No response

5. Do you have any suggestions for a better system of controlling water use?

   22% made some suggestions

6. Do you think you have good water service generally?

   51% said always, 45% usually, 1% half the time, 6 individuals said occasionally, 6 said never, 3% no response

Conclusions from survey

The striking conclusion from the survey was that, despite the rather severe restrictions, or at least the severe financial penalty for exceeding allotments, only 10 percent of the customers considered that they experienced an undue burden in reducing usage by up to 50 percent from corresponding 1976 levels. About half agreed that the same system based on previous use should be used in future droughts while one-third wanted the allotment based upon size of family, one-third wanted it based upon size of yard and some wanted both. The most common criticism of the percent-of-previous-use basis for the allotment was that those who conserved even during wet years, which was the group in which virtually all respondents included themselves, were penalized most while perennial wasters were given bigger allotments. Another complaint was that many believed that late night watering killed their lawns due to fungal growth.

Apparently, many customers eliminated lawn watering almost completely. This appeared to be due to fear of the large penalty for exceeding the allotment combined with lack of knowledge about how to read their meter and ration their water allotment properly, and perhaps lack of time to make the necessary effort.

Another common type of complaint was related to equity questions such as: Why are we restricted when Salt Lake City and Murray are not? Why am I restricted more than my cousin in a different neighborhood? Why aren't you enforcing the penalties on my neighbor who is wasting water?

Despite the long list of complaints, only 22 percent thought the $10 per 1,000 gallon penalty was excessive and only 25 percent thought the night watering hours were unreasonable. In short, based on the survey results, the large majority of water users accepted the District's approach to water management during the shortage. This has some important implications in regard to the system demand functions and hydraulic capacities which are discussed next.

Impact on system demand

As described in a previous section, the SLCWCD restrictions during the summer of 1977 allowed only half of the customers in any neighborhood to water outside on any given day and limited all outside watering to off-peak hours. These voluntary restrictions were not universally followed, but the compliance which was achieved (partly because of the large financial penalty on excessive monthly usage) resulted in dramatic decreases in both monthly use volumes and peak short term flow rates (see Table 3.1).

Table 3.1. Retail deliveries in 1,000 gallons per connection.

Month	1976	1977	% Reduction
May	18.4	17.8	3
June	36.4	23.5	35
July	49.9	31.5	37
August	59.5	29.7	50
September	20.2	29.2	-49 (increase)

The 1977 water volumes delivered to retail customers decreased from 35 to 50 percent from corresponding 1976 levels for the three peak summer months. An interesting result of lifting the restrictions during September 1977 was that conservation not only stopped immediately, but demand actually increased 49 percent above the nondrought year. This was perhaps predictable since many customers probably attempted to revive brown lawns.

The overall deliveries, calculated as retail plus wholesale, for these two years showed a decrease of 28 percent from 26,000 ac ft in 1976 to 18,800 ac ft in 1977. This compares to a 25 percent reduction in retail sales. The annual reduction is less than that during the three peak summer months because nonirrigation month deliveries were essentially equal for the two years.

The most dramatic reduction was in peak daily delivery rates caused by the combination of shifting outside watering to non-peak hours and reducing total water use by the penalty charge. For example, during 1976 the peak inflow to the total system which occurred during at least 3 days, calculated as total spring, well, and treatment plant production, was 123 cfs. This peak was reduced to 72 cfs during 1977, a reduction of 42 percent. The decrease was about 50 percent on many summer days. Since 90 percent of the water users responding to the questionnaire did not experience a serious burden, these figures suggest that this combination of shifting watering periods, surcharges, and penalty charges could be used routinely to reduce flow peaks, making it possible for a utility to serve considerable growth without additional capital investment in water mains and pumps. Considerable cost savings could be passed on to the customer, but water users may not be as responsive to continuing voluntary scheduling to cut utility costs as they were to the short-term drought emergency.

Even though the water volume delivered decreased by 28 percent, the district revenues decreased only 4 percent from \$2,462,150 to \$2,360,820. This relatively small decrease in revenue can be explained by three factors, the least important of which is the revenue from the \$10 per 1,000 gallon penalty. Only 0.2 percent of the total revenue or \$6,500 was collected from penalties because allotments were set high enough that almost no one exceeded them. More important factors were 1) an increase in the price charged for wholesale water, and 2) the higher unit rates which result from a rate schedule spreading the minimum charge over fewer gallons. Rates remained the same, within the allotment, at \$4/month minimum for 10,000 gallons (40 cents per 1,000 gallons) plus 25 cents per 1,000 gallons over 10,000. This meant that as monthly volumes decreased the average unit cost increased from 30 to 34 cents per 1,000 gallons from 1976 to 1977.

Between 1976 and 1977, average monthly volumes decreased from 25.5 to 20 thousand gallons per month in the mixed commercial and residential Granite Park area and from 25.8 to 17.4 thousand gallons in the 1300 East residential area. This 33 percent decrease in annual water use in the residential area is very striking in view of the fact that during 8 months of the year the volumes were essentially the same. The fact that so much conservation could be achieved with so little negative impact on users suggests that the price of water in the SLCWCD, and in most other Utah systems, is so low in comparison to its value to the users that during normal years there is simply no incentive to conserve water.

Impact on Agriculture

Introduction

A letter questionnaire was sent in May 1978 to several thousand farmers and ranchers throughout the State of Utah. The purpose of the survey was to ascertain their opinions about the effect of the 1977 drought on the agricultural sector. Responses were obtained from over 250 persons (about a 5% return), with 242 being complete enough to be used.

The questionnaire was designed to separate the respondents into four categories: 1) a farmer who irrigates, 2) a representative of an irrigation company, 3) a stockman-rancher and 4) a dry farmer. A single respondent could qualify as a member of more than one category. Of the 242 respondents, 220 answered as farmer-irrigators, 183 as representatives of irrigation companies, 146 as stockmen-ranchers, and 59 as dry farmers. Most had multiple functions. Those with only one function were: 66 farmer-irrigators, 15 representatives of irrigation companies, 8 stockmen-ranchers, and 3 dry farmers.

Full time farmers represented 44 percent of the total while 38 percent spent half-time or less in the farming business and 33 percent had other nonfarm employment. Of those responding 53 percent had been in the farming business for 35 years or more and 72 percent were over 50 years of age.

When questioned about their experience with the 1977 drought the following sections summarize the answers of each of the four categories.

Farmer-irrigators

1. Did you experience crop failure (lower yield because of lack of water)?

   24% said None, 10% Slight, 26% Moderate, 33% Severe

2. Did you anticipate a dry year and adjust your planting accordingly?

   71% said Yes, 29% No

   What did you do?

   21% Planted less, 10% Planted different crops, 11% Did not plant, 21% Did other things, 8% No response

3. In a normal year, do you have an adequate water supply?

   66% said All summer, 29% Said it cuts of mid year, 4% Have flood water only

4. In 1977 did you use groundwater?

   21% said Yes, 78% No, 9% Had the same as previous year, 8% More than previous year, 2% It was their only source

5. Did you experience problems over water rights?

   22% said Yes, 78% No

6. Did you apply to appropriate new water?

   15% said Yes, 85% No

7. Was application approved?

   41% said Yes, 45% No, 14% Approved too late

8. Did you apply for government assistance?

   34% said Yes, 66% No

9. Did you receive government assistance?

   32% said Yes, 68% No

Irrigation companies

1. How many stockholders experienced actual crop failure because of water shortage?

   29% said None, 8% 10%, 16% 11-50%, 16% 51-90%, 31% 100% (153 responded)

2. Did the company develop additional water?

   10% said Yes, 90% No (177 responded)

3. Did the company apply for goverment assistance?

   28% said Yes, 72% No (172 responded)

4. Did the company receive government assistance?

   25% said Yes, 75% No

5. Did the company encourage water conservation by asking shareholders to:

   10% said Plant less, 10% Not plant, 7% Shorten water turn,

   48% Better water management, 7% Other, 27% Combination

   (139 responded)

Stockmen-ranchers

1. Did you have animals die because of lack of water?

   3% said Yes, 97% No (146 responded)

2. What was principal effect of drought?

   48% said Lack of feed on range, 17% Lack of watering hole, 1% None, 39% Both (108 responded)

3. Do you haul water?

   35% said No, 14% Every year, 27% Some years, 23% 1977 Only 79 responded

4. Did you develop additional water?

   18% said Yes, 82% No (129 responded)

5. Did you seek government assistance?

   27% said Yes, 73% No (120 responded)

Dry farmers

1. Did you experience crop failure (lower yields) because of lack of water?

76% said Yes, 24% said No (54 responded)

2. How did your crops compare with other years?

12% said Normal, 82% Below, 6% Above (56 responded)

Discussion

About 24 percent of the farmers indicated that they were not damaged by the drought because they had adequate water. Sixty percent received only moderate or no damage, meaning they were able to manage what supply they had. Thirty-three percent reported severe damage--implying that they lost crops or revenue because there was not enough water. The dry farmers probably experienced the greatest crop loss because they had no water to spread through more careful management and their season encompasses the late fall and winter when no rain fell.

The stockmen and ranchers were probably the most distressed although the actual loss of animals was minimal. It was the stockmen who probably received the most immediate relief from governmental assistance. Money to purchase feed, to haul water, or to transport animals to other feeding grounds was made available.

The responses indicated that about 22 percent of the respondents had trouble over water rights. When water is short, and what supply there is must be divided with others, the State Engineer is called upon to make that division. Often he is constrained by a court decree which was written based upon a greater supply than is present during a drought year. Fixed cutoff dates and measurements needed at specified times and places and unyielding distribution ratios between users do not always result in an optimal utilization of the supply. The 1977 season was undoubtedly a busy one for the State Engineer.

This may also account for another problem noted by the respondents. About 15 percent applied to appropriate new water. At the same time they also applied for governmental assistance. About a quarter of these applications which were approved could not be used within the time period set because the approval arrived too late. Others complained that the State Engineer had closed an area to appropriation and therefore prevented new appropriations even though water might have been available.

These commentaries on the returns indicate problems that should be studied before forming policies to deal with future droughts. For additional information on agricultural impacts of the 1977 Utah drought the interested reader is referred to Hughes et al. (1978).

CHAPTER 4

MODEL CHOICE: AN OPERATIONAL COMPARISON OF STOCHASTIC STREAMFLOW MODELS FOR DROUGHTS

Introduction

One can approximate the flood flow for a return period equal to the length of gaged record as being equal to the largest flow recorded during the period of record, but a flood frequency analysis performed by fitting the data of record to a statistical distribution provides a much better estimate. Similarly, one can use the worst drought of record as a basis for water supply design, but assessment of the return period of that design drought requires a model that can generate flow sequences having the same magnitudes and the same patterns as to order as does the historical record. Operational hydrology encompasses a variety of stochastic models for generating synthetic hydrologic time series that the water resource planner may then use to make realistic projections of future water supply conditions and associated estimates of the reliability of the supply and its vulnerability to drought.

In Chapter 2 the application of a seasonal Box-Jenkins model to the Logan River was found to generate less severe periods of water shortage than did the historical record. In this chapter alternative stochastic model structures are investigated to replace the earlier model.

The main purpose of this part of the project work was to compare five stochastic models for generating annual streamflow sequences matching observed historical patterns and to develop a strategy for model selection for desired applications. Each stochastic model was applied to four Utah streams which were selected at locations above which little development has taken place. The annual models used were: second-order autoregressive (AR2), autoregressive moving-average (ARMA), ARMA-Markov (AMAK), fast fractional Gaussian noise (FFGN), and broken line (BKL). The five model applications followed four steps: 1) identification of water resource system and model composition, 2) identification of model form, 3) parameter estimation, and 4) model performance evaluation. Step 1 typically involves decisions about the structure of a water resources simulation model, its inputs, state variables, outputs, and temporal and spatial resolution needed to provide the desired information. Identification of model form (step 2) and parameter estimation (step 3) were undertaken for each annual model and for a disaggregation model. One of two types of disaggregation models was used to divide the generated annual flows into monthly flows. These models are the Valencia-Schaake (VS) and Mejia-Rousselle (MR) models. An additional step between the first and second steps described above is model choice. This step was omitted so that all five annual models could be applied to each study stream and operational comparisons could be made as a basis for the proposed model choice strategy.

Model performance evaluation comprised an evaluation of the preservation of annual persistence statistics and seasonal crossing properties, the cost and ease of model use, and the magnitude of the economic regret associated with drought related agricultural losses, and a comparison of reservoir capacity and critical drought design parameters. The seasonal crossing properties (see Yevjevich 1972 for definitions) evaluated are the expected negative run lengths or drought duration in months and the expected negative run sum in acre feet-months. Both crossing properties were defined with respect to a crossing level set equal to the irrigation water demand for a hypothetical agricultural system and thus the negative run sum is an alternative to the drought severity index defined in Chapter 2. Economic regret was calculated based on agricultural losses estimated using a crop yield model applied to the hypothetical agricultural systems. Economic regret for a given model type is calculated as the sum of the differences between agricultural benefits for the selected model and for all other models. Using the results of the model performance evaluation, a model choice strategy was recommended based on the lag-one autocorrelation ($\hat{\rho}(1)$) and Hurst (K) coefficient values estimated from the historic record.

Selection and Analysis of Streamflow Time Series

The four streamflow time series chosen for study are the Beaver River near Beaver, Utah (1915-1978), Blacksmith Fork above Utah Power and Light Company's Dam, near Hyrum, Utah (1914-1978), the Logan River above State Dam, near Logan, Utah (1901-1978), and Weber River near Oakley, Utah (1905-1978). These streams were selected because 1) their historical records exceeded 60 years in length and therefore they could be expected to provide good estimates of streamflow statistics; 2) there has been no significant upstream development which could be expected to introduce statistical nonhomogeneities into the time series; and 3) they represent a range of values of the lag-one autocorrelation and Hurst coefficients.

An analysis for nonhomogeneities in the historical streamflow records indicated a drop in the mean streamflow of the Logan and Weber Rivers between 1910 and 1920. It was also found that precipitation levels were lower after this period. The records for the Beaver and Blacksmith Fork Rivers did not begin early enough to clearly show this apparent shift.

Table 4.1 contains a comparison of the annual statistics of the historic streamflow records. The calculated statistics indicate

Table 4.1. Comparison of annual statistics of historic streamflow records.

Statistic			Stream			
Symbol	Description	Units	Beaver	Blacksmith Fork	Logan	Weber
N	Length of record used[1]	yrs	64	65	66	74
$\bar{X}$	Mean	ac-ft	36,306	92,659	180,438	158,326
s	Standard deviation	ac-ft	12,706	31,402	47,005	46,570
CV	Coefficient of variation	-	0.35	0.34	0.26	0.29
g	Skew coefficient	-	0.08	0.50	0.15	0.52
$\hat{\rho}(1)$	Lag-one autocorrelation coefficient	-	0.24	0.49	0.32	0.26
H	Hurst coefficient[2]	-	0.61	0.74	0.73	0.84
K	Hurst coefficient[3]	-	0.76	0.76	0.72	0.78
E(RL)	Expected run length[4]	yrs	2.43	3.09	2.29	2.60
E(RS)	Expected run sum[4]	ac-ft-yrs	23,940	69,189	79,809	83,632

[1] Last year of record used was 1978.
[2] H estimator based on pox diagram.
[3] K estimator given in Equation 2.8.
[4] Expected run length and run sum are based on a crossing level of the annual mean flow.

average variabilities as measured by the coefficient of variation. Since the annual skews are low, no attempt was made to use a transformation to account for skew. There is greater variability in the H estimator of the Hurst coefficient than the K estimator, as is characteristic of these estimators (Wallis and Matalas 1970). The values of K are within the range normally found in streamflows (Hurst 1951). Values of the expected run length are quite similar for all four streams, perhaps suggesting that this statistic can be expected to be fairly stable in a given geographic region.

Analysis of the monthly streamflow statistics showed that more than 50 percent of the annual flow occurs in a two or three month period in the late spring. Variability in the monthly flows is greatest during the late spring and early summer as indicated by the standard deviations and coefficients of variation of the monthly flows. The skew coefficient of monthly flows is generally small and positive. The largest values of the skew coefficient generally occur during the spring runoff period and especially in March and June. A Box-Cox transformation (Kottegoda 1980) with $\lambda = 0.33$ was found to minimize the average monthly goodness-of-fit statistic, T, for all study streams. The lag-one autocorrelation coefficient between monthly flows (e.g. between June and July) is consistently high in all except the spring months. The high values occur because of the dominant influence of the groundwater recession in controlling flows in adjacent months. During the spring the influence of the groundwater recession is less than the influence of snowmelt. Correlations between the monthly and annual flow volumes are least in the fall before the winter snow influences runoff, increase in the spring due to the direct influence of snow runoff, and generally continue at the higher levels in the summer under the influence of runoff from the snowpack of the preceding winter.

Annual Streamflow Models

A brief summary of each of the five annual models and the experience gained in applying them to the four study streams is given below. A detailed description of model structure, calibration, and generation procedures for each model is contained in James, Bowles, and Kottegoda (1980).

Second-order autoregressive model

If the streamflow time series exhibits an autocorrelation structure which decays approximately exponentially, the time series can be modeled by an autoregressive model. The second-order autoregressive (AR2) or Markov model was used in this study because all the study streamflows were found to be at least first-order autoregressive and one time series, Blacksmith Fork, appeared to be second-order autoregressive. The AR2 model does not preserve the Hurst phenomenon and therefore generated values of the Hurst coefficient were lower than the historical values.

ARMA(1,1) model

O'Connell (1974) evaluated the autoregressive moving average (ARMA) family of models proposed by Box and Jenkins (1970) for their suitability in preserving long-term persistence as represented by the Hurst coefficient, and recommended use of the ARMA (1,1) model. This model has first-order autoregressive and moving average terms, and a parameter must be estimated for each. To accomplish this, the AR parameter (ϕ) must have a value close to unity, so that the autocorrelation function (ACF) of the ARMA process will attenuate slowly and hence approximate the theoretical ACF (TACF) of FGN.

The parameters ϕ and Θ (moving average parameter) of the ARMA model which will preserve a given combination of the lag-one autocorrelation ($\rho(1)$) and Hurst coefficients were derived by O'Connell (1974) on the basis of a large number of Monte Carlo experiments. The appropriate values for ϕ and Θ can be obtained from his tables based on the values of $\rho(1)$ and the Hurst coefficient to be preserved. Since O'Connell's experiments were based on sequences of length, 25, 50, and 100 years, which are not equal in length to those used in this study, it was necessary to refine the interpolated values of ϕ and Θ by Monte Carlo generation using sequences equal in length to the historic record and based on the criterion of preserving $\rho(1)$ and the K estimate of the Hurst coefficient.

ARMA-Markov model

The ARMA-Markov model (AMAK) was developed by Lettenmaier and Burges (1977) as an alternative approximation for fractional Gaussian noise. It is a combination of the ARMA (1,1) model used by O'Connell (1974) and the Markov or first-order autoregressive model. The AMAK model attempts to satisfy the requirements for modeling both high and low frequency persistence as well as being economical to use in terms of computer time. An advantage of the AMAK model is that the Hurst coefficient is an explicit parameter as it is for FGN models. The AMAK model utilizes the ACF of the ARMA (1,1) process to preserve long-term persistence at high lags. The parameters of the AMAK model are estimated by fitting the TACF of FGN at three arbitrarily selected lags.

The AMAK model is defined as follows:

$$X_t = \mu + \rho_M(X_{t-1}^{(M)} - \mu) + \varepsilon_t^{(M)} + \phi(X_{t-1}^{(AM)} - \mu) + \varepsilon_t^{(AM)} - \Theta\varepsilon_{t-1}^{(AM)} \quad \ldots \ldots \ldots \quad (4.1)$$

in which

X_t = streamflow values in time period t

μ = mean of X_t

ρ_M = Markov model parameter

ϕ = AR model parameter

Θ = MA model parameter

M = label for Markov terms

AM = label for ARMA (1,1) terms

$\varepsilon_t^{(M)}$ and $\varepsilon_t^{(AM)}$ are independent processes having the following variances:

$$\sigma_\varepsilon^2 = C_1 (1 - \rho_M^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.2)$$

$$\sigma_\varepsilon^2 = C_2 \frac{(1 - \phi^2)}{1 + \Theta^2 - 2\phi\Theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.3)$$

in which

C_1 = fraction of variance explained by Markov component

C_2 = fraction of variance explained by ARMA (1,1) component

Three alternative methods of parameter estimation of C_1, C_2, ρ_M, ρ_M and ϕ. were used in this study. Each method is described below and is denoted by the name of its originator. The first two methods are designed to fit the autocorrelation function of the AMAK model to the TACF of FGN. The third method, proposed in James, Bowles, and Kottegoda (1980), attempts to preserve only $\rho(1)$ and the Hurst coefficient.

Lettenmaier and Burges' method. The LB method was proposed by the originators of the AMAK model (Lettenmaier and Burges 1977) and is based on fitting the TACF of FGN at three arbitrary lags ℓ_1, ℓ_2 and ℓ_3. Lettenmaier and Burges found it convenient to use lags of N/8, N/2, and N where N is the length of the sequence being generated. Parameter estimation by the LB method requires the solution of the five simultaneous equations.

Kottegoda's method. The second parameter estimation procedure for the AMAK model was recommended by Kottegoda (1980). The method is based on a visual fitting of the first nine lags of the TACF of FGN to the ACF of the AMAK model. The fitting of the AMAK ACF to the FGN TACF could be automated using a curve fitting procedure.

James' method. The third method of parameter estimation involves the following steps (James et al. 1980):

1) Set ρ_M equal to $\rho(1)$, the historic estimate of the lag-one autocorrelation coefficient.

2) Select ϕ and Θ using O'Connell's (1974) parameter estimation procedure for the ARMA (1,1) model which is based on preserving (1) and K estimated from the historic record.

3. Set C_1 by trial and error fitting of $\rho(1)$ and K based on analysis of the values of $\rho(1)$ and K preserved in generated sequences and calculate $C_2 = 1 - C_1$.

Comparison of the three parameter estimation methods indicates that the James' method generally provides parameter estimates which do a better job of preserving $\rho(1)$ and K values as would be expected since it is based on preserving these parameters. Experience also demonstrated that the James' method was the easiest to apply. Model applications calibrated by the LB method led to lower values of $\rho(1)$ and in several cases gave very little weight to the Markov component due to small estimates of C_1. However, in this study the values of $\rho(1)$ and K computed from the generated sequences were found to be relatively insensitive to the values assigned to C_1 and C_2. The generated persistence statistics were generally very close to their historic values.

Fast fractional Gaussian noise model

Mandelbrot (1971) developed an approximation to the ACF of the discrete time fractional Gaussian noise (dFGN) process and called it fast fractional Gaussian noise (FFGN). The model is essentially a sum of high and low frequency terms, the high frequency represented by a lag-one Markov process and the low frequency represented by a weighted sum of several lag-one Markov processes specified by a choice of two parameters called the base, B, and the number of low frequency terms, L.

Trial-and-error calibration of the FFGN model to the study streams lead to the following parameter assignments: B = 2.0, L = 10, and $\rho^{(HF)}(1)$, the lag-one autocorrelation coefficient of the high frequency term, equal to the historic estimate of $\rho(1)$. Conventionally $\rho^{(HF)}(1)$ is calculated as a function of the lag-one autocorrelation coefficients and variances of the L low frequency terms (Chi et al. 1973). However, it was found in this study that the resemblance of $\rho(1)$ and K was generally improved by setting $\rho^{(HF)}(1)$ equal to the historic estimate of $\rho(1)$. Two of the study streams, Beaver and Weber, fall outside the feasible $\rho(1)$-K region for the FFGN model. The generated $\rho(1)$-K points tend to be grouped close to the TACF of FFGN.

Broken line model

The general broken line (BKL) flow generating process developed by Mejia et al. (1972) is the sum of NL+1 simple broken line process. A simple broken line process is derived from linear interpolation between uniformly spaced independent Gaussian variates. The spacing of the independent variates differ for each simple broken line but are functionally related to the spacing, a_1, of the first line. The high frequency properties of BKL model are a function of the short simple broken lines and the low frequency properties are a function of the long simple broken lines. In this study a modification proposed by Curry and Bras (1978) was incorporated to minimize the effect on $\rho(1)$ caused by the low frequency terms. The modification is the addition of a high frequency simple broken line with parameter a_0.

Parameter estimation for the BKL model requires fitting the historic lag-one autocorrelation and Hurst coefficients to the BKL lag-one autocorrelation coefficient. An alternative fitting procedure is to preserve $\rho''(0)$, the second derivative of the lag-zero autocorrelation coefficient at the origin, instead of the Hurst coefficient. However, since this derivative does not exist for discrete series, such as annual streamflow volumes, this procedure was not adopted. Experience gained in calibrating to the study streams indicated that using a value of NL which maintained the parameter a_1 between 1 and 2 usually led to a more accurate preservation of the persistence statistics. The BKL was not capable of preserving the high lag-one autocorrelation coefficient of 0.49 for Blacksmith Fork, unless a_0 was set equal to a_1.

Monthly Streamflow Models

Monthly flow volumes were needed in order to evaluate the impact of drought at different stages of crop growth. Disaggregation models were used to divide the generated sequences of annual flows into monthly flows while preserving some of the important correlation relationships 1) between monthly flow volumes and 2) between monthly and annual flow volume. Two alternative seasonal disaggregation models were used: the Valencia-Schaake (VS) model (Valencia and Schaake 1973) and the Mejia-Rousselle (MR) model (Mejia and Rousselle

1976). The MR model is similar to the VS model except that it adds a term to preserve some of the serial correlations between adjacent months in successive water years. The additional term is a function of Z_t, the vector of standardized flow volumes for the last m months of the previous year.

In estimating the parameter matrices $\underline{B}$ and $\underline{E}$ (see James, Bowles, and Kottegoda 1980) for the VS and MR models, respectively, it is necessary to solve an equation in which the unknown term is in the form $\underline{BB}^T$ (or $\underline{EE}^T$). As a necessary condition for obtaining a real-valued solution for $\underline{B}$ (or $\underline{E}$) the matrix $\underline{BB}^T$ (or $\underline{EE}^T$) must be positive semidefinite (psd), that is, all of its eigen values must be positive. When parameter estimation of the MR model was attempted for the four study streams it was found that in some cases solutions for $\underline{E}$ could not be obtained because $\underline{EE}^T$ was non-psd. After some investigation of this problem it was discovered that the following factors affected the degree to which $\underline{EE}^T$ was non-psd or psd as measured by the smallest eigen value of $\underline{EE}^T$:

1) The Box-Cox transformation parameter, λ.

2) The starting year (or more generally the interval) of the historical record used to estimate the parameter matrices.

3) The number of months, m, in the (t-1)st year which are included in $\underline{Z}_t$.

To help understand what might be done to overcome this difficulty in parameter estimation, a procedure was devised to examine the influence of the above three factors on obtaining a solution for $\underline{EE}^T$. The procedure is represented schematically in Figure 4.1. Essentially it attempted to obtain real-valued solutions for $\underline{E}$ with various combinations of values for λ and m. The degree of success in obtaining a real-valued solution for $\underline{E}$ was measured by the magnitude of the smallest eigen value of $\underline{EE}^T$. If it was not possible to obtain a real-valued solution for $\underline{E}$ in the MR model then the feasibility of a real-valued solution for $\underline{B}$ in the VS model was examined. If real-valued solutions for neither $\underline{E}$ or $\underline{B}$ could be obtained then a new starting year was used in taking data from the record.

Table 4.2 summarizes some attempts to obtain real-valued parameters for the disaggregation models. Reductions in the size of λ decreased the size of the smallest eigen value but never resulted in a change in sign. Increases in m reduced the magnitude of the smallest eigen value and eventually resulted in a negative value. The largest values of m that resulted in real-valued solutions for $\underline{E}$ were: 3 for Beaver, 0 for Blacksmith Fork, 2 for Logan, and 2 for Weber. The value of m=0 for Blacksmith Fork indicates that in no case was parameter estimation successful with the MR model and therefore the VS model was used. Parameter estimation for Logan was successful only after the starting year was changed from 1901 to 1913 to avoid an early period of high flows.

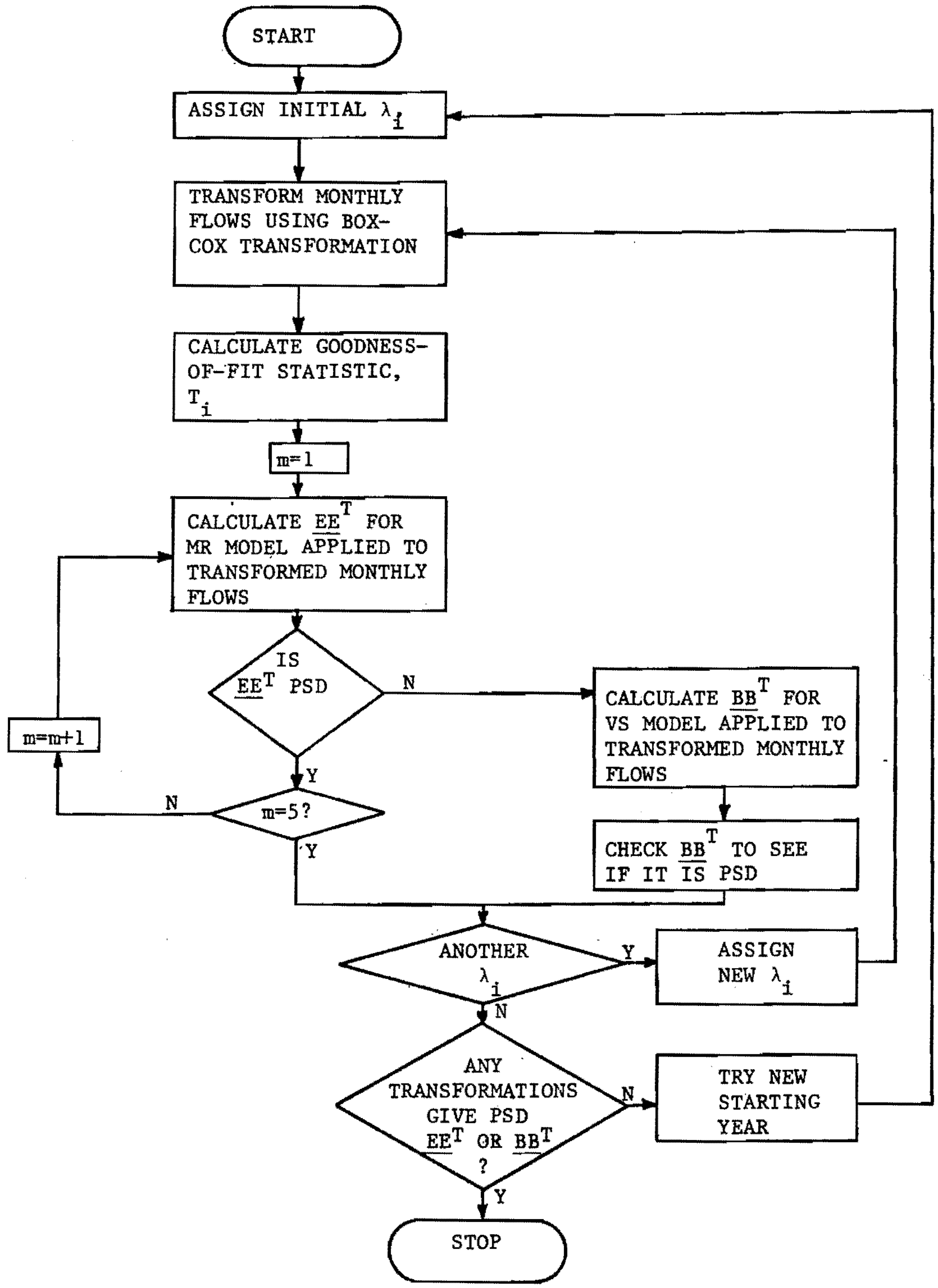

Figure 4.1. Procedure for examining the influence of several factors on parameter estimation for disaggregation models.

Table 4.2. Summary of attempts to obtain real-valued parameters for disaggregation models.

Stream	Case No.	Starting year used	Disaggregation model[1]	Number of months in previous year (m)	Box-Cox Transformation Parameter (λ)	Smallest Eigen Value[2]	Goodness-of-fit (T) Average Year	Goodness-of-fit (T) Average growing season
Beaver	1	1915	MR	1	0.333	0.285	-0.040	-0.006
	2	1915	MR	2	0.333	0.185	-0.040	-0.006
	3[4]	1915	MR	3	0.333	0.054	-0.040	-0.006
	4	1915	MR	4	0.333	-0.181	-0.040	-0.006
Blacksmith Fork	1	1914	MR	1	0.200	-0.113	-0.014	-0.007
	2	1914	MR	1	0.150	-0.048	-0.022	-0.018
	3	1914	VS	-	-[3]	0.001	0.122	0.157
	4[4]	1914	VS	-	0.333	0.102	0.010	0.022
	5	1924	MR	1	0.333	-0.507	0.010	0.022
	6	1924	MR	1	0.200	-0.044	-0.014	-0.007
	7	1924	MR	1	0.150	-0.017	-0.022	-0.018
	8	1924	MR	1	0.100	-0.007	-0.031	-0.028
Logan	1	1913	MR	1	0.333	0.103	-0.041	-0.078
	2[4]	1913	MR	2	0.333	0.108	-0.041	-0.078
	3	1913	MR	3	0.333	-0.238	-0.041	-0.078
	4	1913	VS	-	0.333	0.163	-0.041	-0.078
	5	1923	MR	1	0.333	-0.141	-0.041	-0.078
	6	1923	MR	2	0.333	-0.469	-0.041	-0.078
	7	1923	MR	1	0.250	-0.033	-0.052	-0.092
	8	1923	MR	1	0.200	-0.014	-0.059	-0.101
	9	1924	MR	1	0.200	0.010	-0.059	-0.101
	10	1924	MR	2	0.200	0.009	-0.059	-0.101
	11	1924	MR	2	0.333	0.099	-0.041	-0.078
	12	1924	MR	3	0.333	-29.330	-0.041	-0.078
Weber	1	1905	MR	1	0.333	0.774	0.018	-0.033
	2[4]	1905	MR	2	0.333	0.478	0.018	-0.033
	3	1905	MR	3	0.333	-0.663	0.018	-0.033

[1] VS = Valencia-Schaake, MR = Mejia-Rousselle.
[2] Eigen value for $\underline{EE}^T$ for MR model and for $\underline{BB}^T$ VS model.
[3] No transformation used for this case.
[4] This is the case selected for use.

Examination of Table 4.2 indicates several successful cases of parameter estimation for each stream. The cases selected for use are labeled by footnote 4 in the column labeled "Case No.". These cases were selected to keep the same value of λ for all streams for comparative purposes, to keep m as high as possible to give the best preservation of over-the-year serial correlations, and to make use of the longest length of homogeneous historical record to improve parameter estimates. As an example of the disaggregation performance, Figure 4.2 contains graphical comparisons of several historic and disaggregated monthly statistics for Beaver River. The disaggregated statistics are based on applying several disaggregation models to the historical annual flow volumes. For all four study streams the disaggregated means and standard deviations are very close approximations to the historical values in all months. Disaggregated values of the skew coefficient do not closely approximate the historical values because the same value of λ was used for all 12 calendar months and it was not the best value for every month although it did minimize the monthly goodness-of-fit statistics, T, averaged over the year (see Table 4.2). In general, months with lower skew coefficients were modeled better than months with higher skew coefficients. Monthly values of S_{YX}, the cross-correlation between annual and monthly flows, are quite well preserved for all streams as would be expected since this parameter is explicitly incorporated into the parameter estimation for both the MR and VS models.

The lag-one serial correlation between months, r(1), is explicitly incorporated into the parameter estimation for the MR model and consequently the disaggregated values closely resemble the historic values. However, as would be expected due to its lack of capability for preserving over-the-year serial correlations disaggregated flows from the VS model do not resemble the historic value of r(1) at the beginning of the water year.

Agricultural Economic Loss Model

Most evaluations others (e.g. Burges and Lettenmaier 1975) have made of stochastic streamflow models have emphasized preservation of statistics of the streamflow time series and compared relationships between preserved statistics and the reservoir capacities estimated as required to develop a given firm yield. In this study, model performance was also compared through estimates of economic regret measured in terms of the losses in the value of agricultural production. A diversion rule was applied to the generated monthly streamflows to calculate monthly diversions available for irrigation. The quantity of water available for diversion and the irrigation water requirement were used as inputs to an agricultural economic loss model for estimating crop yield and the decrease in the value of agricultural production during water short years.

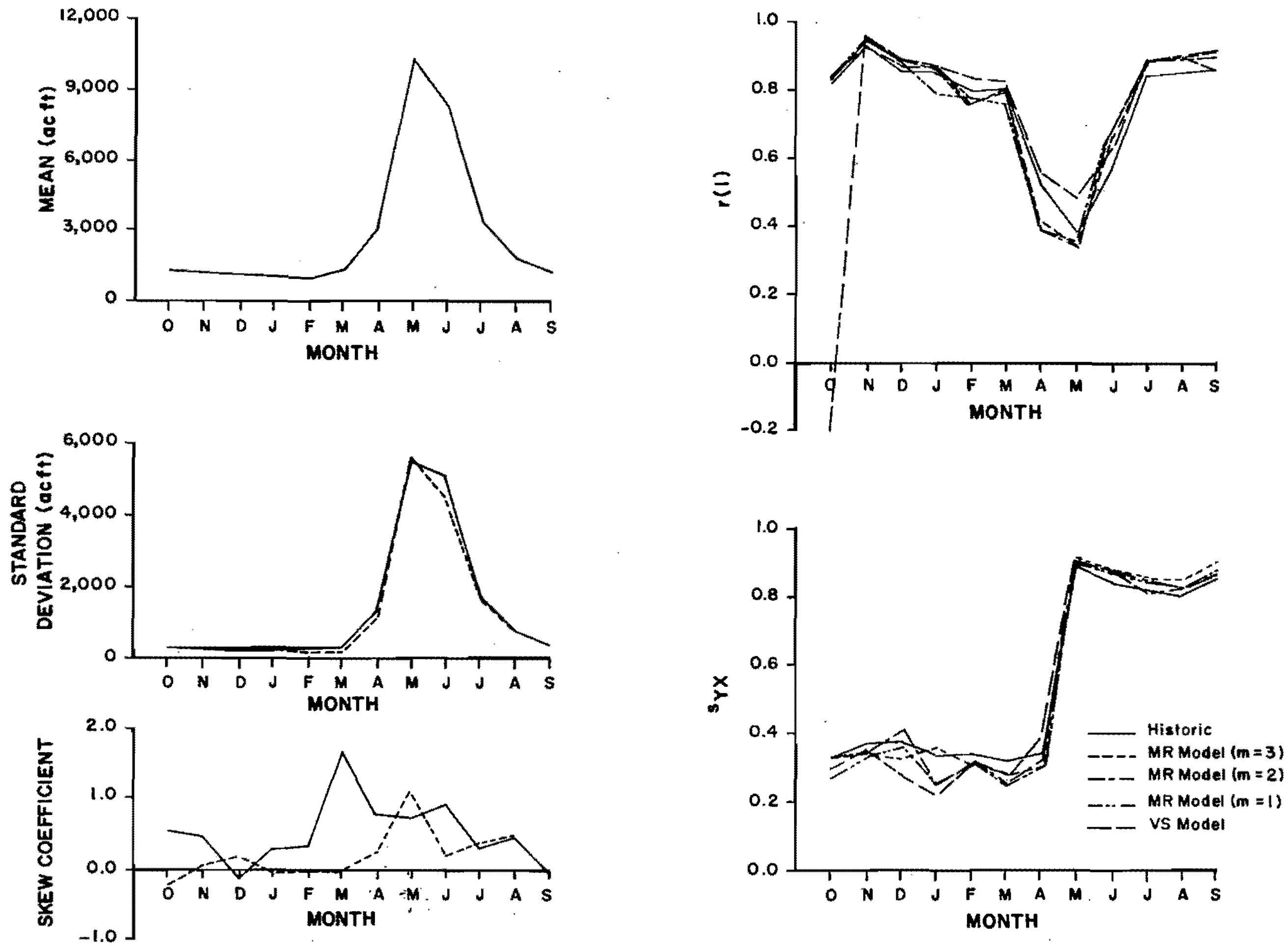

Figure 4.2. Comparison of historic and disaggregated monthly statistics for Beaver.

A crop yield model developed by Hanks (1974) and parameterized for grain corn by Gowon et al. (1978) was selected as a basis for the agricultural loss function. The model relates the yield of grain corn to the ratio of actual to potential evapotranspiration in three crop growth stages as follows:

$$Y = 0.97\ R_v^{0.347}\ R_p^{0.574}\ R_m^{0.330}\ Y_p \quad . \; . \; . \; . \; . \; . \; . \qquad (4.4)$$

in which

Y = yield of harvested grain corn (bushels/acre)

YP = potential yield based on the highest measured yield for grain corn at the study location (bushels/acre)

R = ratio of actual to potential evapotranspiration

v = subscript denoting vegetative growth stage of grain corn (May and June)

p = subscript denoting pollination growth stage of grain corn (July)

m = subscript denoting maturation growth stage of grain corn (August and September)

Grain corn was chosen because it is a highly drought sensitive crop. Actual evapotranspiration was calculated based on an irrigation diversion rule applied to the monthly generated streamflows and assuming an irrigation efficiency of 50 percent. Values of potential evapotranspiration for each growth stage were calculated using the modified Blaney-Criddle method for estimating consumptive use.

The average annual economic benefit or value of the crop is estimated by the following expression in which any effect on production costs of the availability of irrigation water is neglected:

$$B_j = \frac{1}{N} \sum_{t=1}^{N} Y_t\ P\ A \quad . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (4.5)$$

in which

B_j = average annual economic benefit based on streamflows generated by model j

N = length of generated streamflow sequence

t = year index

Y_t = crop yield for i^{th} year

P = price of grain corn

A = irrigated area

Thus, different values of B_j can be calculated using the generated sequences from the five annual streamflow models and also using the historic streamflow sequence.

If model i represents the true streamflows but the planner is instead using the flows generated by model j, economic regret is the difference in the value of B_j based on streamflows generated with model j assuming that model i is the true model. Thus economic regret is defined as follows:

$$\alpha_{ij} = B_i - B_j \quad \text{. . . . .} \quad (4.6)$$

in which

α_{ij} = economic regret for model i given that model j is true

Since in practice we do not know which model is true, or perhaps more accurately, which model best represents the actual streamflow generating process, it is useful to calculate a total economic regret by assuming that each alternative model and the historic sequence is true, in turn, as follows:

$$R_i = \sum_{j=1}^{M} \alpha_{ij} = \sum_{j=1}^{M} (B_i - B_j) \quad \text{. . . . . . .} \quad (4.7)$$

in which

R_i = total economic regret for model i

M = number of alternative models including the historic sequence

The α_{ij} are summed algebraically and thus R_i can be positive or negative. It follows that the most desirable model, based on this criterion, is the one that minimizes the absolute value of R_i.

Comparison of Annual Model Performance

Annual model performance was evaluated with respect to the five factors listed in the introduction of this chapter. Each factor will be considered separately below.

Evaluation of annual performance

Summary statistics for comparing the historic and generated annual statistics are shown in Table 4.3. The match between historical and generated series was compared in terms of Type B resemblance (O'Connell 1974), wherein the models were used to generate 50 series of length equal to the historical record. The lag-one autocorrelation and Hurst coefficients were calculated for all 50 series. Then the means and standard deviations of both coefficients over the 50 series were calculated. The generation procedure used in this study ensured that the coefficient of variation of the streamflows is always preserved (see James, Bowles, and Kottegoda 1980). The preservation of $\rho(1)$ and K was generally good for the FGN approximations (i.e. FFGN, ARMA, AMAK, BKL) but poor for the AR2 model. All models tended to underestimate the biased lag-one autocorrelation, possibly due to the small number of traces (O'Connell 1974). For the Hurst coefficient all models except ARMA underestimated K for the Beaver and Weber streamflows. For the Blacksmith and Logan the generated values of the Hurst coefficient were distributed above and below the historic values. In all cases the ARMA model gives the highest average estimate for the Hurst coefficient, providing the closest fit for Beaver and Weber. The lower lag-one autocorrelation coefficients for Beaver and Blacksmith were generally preserved better than the higher values. For the Hurst coefficient, the best fit was for Logan which has an historic Hurst coefficient of 0.72 which is in the known unbiased range (Wallis and Matalas 1970). As would be expected, the AR2 model did poorly in preserving the Hurst coefficient. The BKL model consistently underestimated the Hurst coefficient for all the streams except Logan. With the exception of the BKL model for the Beaver and Weber, the AR2 and BKL models underestimated the lag-one autocorrelation coefficient. In most cases the models preserved the lag-one autocorrelation and Hurst coefficients within one standard deviation (see Table 4.3 for values of $\rho(1)$ and K). The exceptions were: the AR2 Hurst coefficient for the Beaver, the ARMA Hurst coefficient for the Blacksmith Fork, and the AR2 Hurst coefficient for the Weber. However, for all of these exceptions the generated values were within two standard deviations of the historic values.

The foregoing statements describe model performance with respect to preserving either $\rho(1)$ or K separately. The rankings in Table 4.4 provide a means of evaluating model performance with respect to preserving $\rho(1)$ and K simultaneously. For the equal weighting case the criterion for selecting the best model is that it minimizes the

Table 4.3. Overall summary of model results.

		Annual Statistics					Demand	Irrigation Season Statistics				Design Parameters			
Stream	Model	$\bar{CV}$[1]	$\bar{\rho}(1)$[2]	$\tilde{\rho}(1)$[3]	$\bar{K}$[4]	$\tilde{K}$[5]	D^*[6]	E(ND)[7]	E(RL)[8]	E(RS)[9]	Total Economic Regret[10]	Reservoir design capacity[11] S^*_{98}	Reliability of Historic storage estimate S^*[12]	Critical drought[13] CD^*_{98}	Probability of non-exceedance of historic critical drought CD^*[14]
Beaver	Historical	0.35	0.24	-	0.76	-	0.49	48	2.15	0.14	-	(0.58)	-	(0.36)	-
	AR2	0.35	0.19	0.09	0.66	0.06	0.49	46.68	2.33	0.14	5,100	1.08	45	0.97	7
	ARMA	0.35	0.20	0.15	0.78	0.07	0.49	46.48	2.35	0.14	-4,500	1.24	41	0.98	12
	AMAK	0.35	0.23	0.15	0.73	0.08	0.49	46.64	2.35	0.14	-900	1.17	50	0.96	16
	FFGN	0.35	0.33	0.13	0.75	0.07	0.49	47.06	2.32	0.13	6,900	1.15	48	0.86	6
	BKL	0.35	0.24	0.11	0.72	0.08	0.49	46.22	2.32	0.13	-8,100	1.05	49	0.89	9
Blacksmith Fork	Historical	0.34	0.49	-	0.77	-	0.71	46	2.02	0.14	-	(0.59)	-	(0.38)	-
	AR2	0.34	0.43	0.11	0.74	0.07	0.71	41.86	2.02	0.15	-17,700	2.16	14	1.19	15
	ARMA	0.34	0.49	0.16	0.84	0.06	0.71	41.52	2.03	0.15	-15,900	2.79	13	1.57	20
	AMAK	0.34	0.46	0.12	0.80	0.07	0.71	42.20	2.02	0.15	13,500	2.36	13	1.31	23
	FFGN	0.34	0.44	0.10	0.78	0.06	0.71	41.82	2.01	0.15	-1,500	2.04	19	1.15	17
	BKL	0.34	0.48	0.12	0.76	0.07	0.71	42.30	2.01	0.15	-900	1.93	14	1.08	14
Logan	Historical	0.26	0.32	-	0.72	-	0.84	59	2.17	0.22	-	(0.60)	-	(0.55)	-
	AR2	0.26	0.26	0.11	0.68	0.07	0.84	61.10	2.13	0.21	-35,000	1.29	12	0.85	24
	ARMA	0.26	0.28	0.13	0.74	0.07	0.84	61.28	2.13	0.21	-41,000	1.46	13	0.88	14
	AMAK	0.26	0.30	0.12	0.72	0.06	0.84	61.26	2.17	0.21	31,000	1.60	16	1.02	27
	FFGN	0.26	0.34	0.15	0.74	0.07	0.84	60.84	2.16	0.21	-11,000	1.31	20	0.81	29
	BKL	0.26	0.24	0.13	0.72	0.07	0.84	60.78	2.18	0.21	7,000	1.46	15	0.83	22
Weber	Historical	0.29	0.27	-	0.78	-	0.45	60	2.08	0.08	-	(0.30)	-	(0.30)	-
	AR2	0.29	0.22	0.10	0.69	0.07	0.45	58.48	1.94	0.09	-52,000	0.53	17	0.48	9
	ARMA	0.29	0.30	0.16	0.80	0.07	0.45	57.78	1.96	0.09	-64,000	0.53	14	0.49	10
	AMAK	0.29	0.27	0.12	0.77	0.06	0.45	57.94	1.94	0.09	-70,000	0.51	14	0.49	13
	FFGN	0.29	0.33	0.12	0.74	0.07	0.45	57.50	1.95	0.09	-100,000	0.49	14	0.49	19
	BKL	0.29	0.28	0.13	0.75	0.06	0.45	58.38	1.95	0.09	-46,000	0.49	16	0.49	17
Column No.		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)

1 Expected value of coefficient of variation of annual streamflow volumes
2 Expected value of annual lag-one autocorrelation coefficient
3 Standard deviation of lag-one autocorrelation coefficient
4 Expected value of Hurst coefficient
5 Standard deviation of Hurst coefficient
6 Seasonal demand divided by mean seasonal diversions (see Table 6.2) (James, Bowles, and Kottegoda 1980)
7 Expected number of down crossings or droughts in the synthetic sequences with length equal to the historic record at seasonal demand level in column 6
8 Expected seasonal negative run lengths with respect to demand level in column 6
9 Expected seasonal negative run sum divided by mean seasonal diversion with respect to demand level in column 6
10 Economic regret calculation in Table 7.3 (James, Bowles, and Kottegoda 1980)
11 Reservoir design capacity divided by average seasonal diversion at 98 percent reliability for each model. Note that for historic case reservoir storage is based on streamflow record and with estimates of its reliability given in column 12
12 Percent reliability of reservoir estimated from historic record
13 Critical drought (maximum negative run sum) based on 98% probability of nonexceedance divided by average seasonal diversion for each model. Note that for historic case critical drought is based on streamflow record and with estimates of its reliability given in column 13
14 Probability of nonexceedance of historic critical drought (maximum negative run sum)

Table 4.4. Ranking of models by alternative model choice criteria.

Stream	Ranking	Criterion for ranking: Persistence Statistics: $\rho(1)$ - K — Equal weighting Min $(\Delta\rho(1) + \Delta K)$	Criterion for ranking: Persistence Statistics: $\rho(1)$ - K — Unequal weighting Min $(0.15\ \Delta\rho(1) + \Delta K)$	Total Economic Regret — Minimum
Beaver	1st	ARMA	FFGN	AMAK
	2nd	AMAK	ARMA	ARMA
Blacksmith Fork	1st	AMAK	FFGN	BKL
	2nd	BKL	BKL	FFGN
Logan	1st	ARMA	AMAK	BKL
	2nd	AMAK	BKL	FFGN
Weber	1st	AMAK	AMAK	BKL
	2nd	FFGN	ARMA	AR2

sum of the errors between the generated and historical values of $\rho(1)$ and K. In the unequal weighting case the error in preserving $\rho(1)$ is weighted by 0.15 to reflect its smaller influence in determining reservoir size relative to the influence of K (see James, Bowles, and Kottegoda 1980). In neither the equal nor unequal weighting case is any model consistently ranked first or second for all four study streams. However, the AMAK model is ranked either first or second for all but one of the two weighting cases for the three streams, and therefore the AMAK model was judged the overall best based on its ability to preserve $\rho(1)$ and K. The ARMA model was judged the overall second best model. Several limitations should be borne in mind with regard to the generality of this assessment of the performance of the AMAK and ARMA models. It cannot be concluded that they are the best models for any stream as can be seen from the fact that AMAK is ranked first in only 50 percent of the study cases and ARMA in only 25 percent of the cases. The general desirability of these models above the alternative models based on application to a wide range of streamflow sequences has not been demonstrated in this study or elsewhere at this time. It should also be noted that there is a subjective element in the calibration of the AMAK and ARMA models, and this study has not addressed the influence of this subjective element on the high ranking of the AMAK and ARMA models. The five annual models were not evaluated based on their preservation of autocorrelations other than lag-one, and therefore no conclusions can be made with regard to their ability to preserve the general autocorrelation structure of the historic streamflow time series.

Evaluation of seasonal performance

A summary of the historic and generated irrigation season statistics is included in Table 4.3. The irrigation season statistics are: E(ND), the expected number of down crossings or droughts in the N year synthetic sequences, E(RL), the expected negative run length or drought duration in months and E(RS), the expected negative run sum or drought severity. These statistics, which are contained in columns 7, 8, and 9, respectively of Table 4.3, are drought crossing properties with respect to a crossing level defined by the agricultural demand or irrigation requirements (see column 6, Table 4.3) during the irrigation season. There is very little variation in the generated values of the three irrigation season statistics between models for the same study stream. For all streams except Logan the E(ND) are slightly less than the historic number of droughts. The E(RL) values for the Beaver are a little greater than historic RL, and for the Blacksmith and Logan the E(ND) are approximately equal to their respective historic RL. The E(RS) for the Beaver are approximately equal to the historic, for the Blacksmith and Weber the E(RS) are slightly greater than the historic, and for the Logan the E(RS) are slightly less than the historic. Thus the drought crossing properties do not appear to be very sensitive to either the choice of the annual model or the values of the lag-one autocorrelation and Hurst coefficients which are preserved.

Evaluation by cost and ease of use

In addition to the adequacy of the performance of the annual models the cost and ease of their use must be considered when selecting a model. The AR2, ARMA, and AMAK models are the least expensive to run and the FFGN is the most expensive, costing almost six times as much as the AR2. The level of effort required for parameter estimation varies from model to model. Most time consuming in this regard are the BKL and AMAK models which require the use of separate programs for the estimation of model-specific parameters beyond the usual statistical moments and Hurst coefficient. Parameter estimation for the ARMA model can also require a moderate level of effort if values for ϕ and Θ interpolated from O'Connell's (1974) tables must be refined through Monte Carlo simulation for the sequence length and number of traces to be used in a particular application.

Comparison of design parameters

Two design parameters have been calculated based on the monthly flow volumes obtained by disaggregating the annual synthetic streamflow sequences generated by the five annual models. These parameters are the reservoir design capacity and the critical drought volume.

The reservoir design capacity associated with a particular reliability of supply is obtained from a probability distribution of reservoir storage volumes which are required to completely satisfy the irrigation water requirements for a hypothetical agricultural system. The reservoir storage volumes are obtained from applying the sequent peak algorithm to each of the 50 synthetic sequences. The reservoir storage volumes were fitted to a Gumbel distribution and a design capacity at a 98 percent reservoir reliability was calculated. A dimensionless storage ratio, S*, was obtained by dividing the storage volumes by the mean irrigation season diversion for each stream.

To obtain the critical drought volume, a probability distribution of the largest negative run-sums from each of the 50 synthetic traces was plotted. The negative run-sums or drought deficits were calculated with respect to the monthly irrigation requirements for each study stream. The critical drought volume, CD_{98} was read from the distribution at the 98 percent probability of nonexceedance. Adoption of a 98 percent probability of nonexceedance was arbitrary in this case. It was found that the run-sums approximately followed the extreme value type I distribution which is not surprising because of the close relation of these negative run-sums and the reservoir storage volumes: both are range statistics. A dimensionless drought ratio, CD*, was obtained by dividing the drought deficits by the mean irrigation season diversion for each stream.

Plotted distributions of S* and CD* were obtained by the frequency factor approach of Chow (1951). Values of S^*_{98} and CD^*_{98} obtained from the probability plots are given in columns 11 and 13 of

Table 4.3, respectively. An examination of the ranking of these values reveals a fairly consistent trend which is similar for both design parameters and all study streams. The ARMA and AMAK models give the largest or most conservative values, the FFGN and BKL models the smallest or least conservative values, and the AR2 model generally gives values which lie in between those from the other models. It is interesting to note that since the ARMA and AMAK models were judged overall best in preserving the persistence statistics, the conservative estimates of the design parameters may be the most reliable.

Also presented in Table 4.3 in the runs labelled "Historical" are the reservoir design capacity and largest negative run-sum obtained from the historical streamflow records (columns 11 and 13, respectively). Comparison of these values with the values obtained from the synthetic sequences indicates that the historical values are much smaller in all cases. Another way of illustrating this same point is by obtaining the probability of nonexceedance (reliability for S*) for S* and CD* from the probability plots. These probabilities are given for each stream in columns 12 and 14 of Table 4.3 based on each model. In all cases the probabilities are much less than the 98 percent values of the design parameters and therefore the historic values of the design parameter are less than the mean of the distributions of these parameters obtained from the stochastic generation. This is in contrast to the results reported in Chapter 2 for the multiplicative ARMA model for which generated sequences were much less severe than the historic.

Evaluation by economic regret

For each stream the two models with the lowest total economic regret are listed in Table 4.4. The BKL model minimizes economic regret for all streams except the Beaver and is clearly the overall best model with respect to the regret criterion. The FFGN model appears to be the overall second best model. It is observed in Table 4.4 that for the Beaver the ARMA model was ranked first or second by all three criteria, and for Blacksmith Fork the FFGN model was similarly placed. Also for three out of four of the study streams the same model is ranked first or second by the economic regret and by at least one of the persistence statistics criteria. Although the BKL model is ranked first for three out of four of the study streams based on economic regret it appears only once in second place based on the persistence statistics criteria. In fact the economic regret and persistence statistics criteria did not select any of the same overall best models. This implies that the objective of preserving the persistence statistics is not compatible with the objective of minimizing economic regret for the study streams. It should be noted that this conclusion is subject to the same limitations with respect to its generality as were discussed in the section on "Evaluation of annual performance." The low estimates of regret obtained from the BKL and FFGN models results from the tendency of these models to generate droughts with severities of magnitudes in between those generated by the other models. It should be noted that this property does not conflict with the fact that the BKL and FFGN models gave the smallest values of S^*_{98} and CD^*_{98} since these are extreme value statistics and economic regret is not.

A Model Choice Strategy

Selection of a stochastic streamflow model for data generation should consider the following factors:

1) Ability to preserve relevant statistical characteristics of the historic streamflow time series.

2) Cost of using the technique measured in terms of computer costs and labor costs for calibration.

3) Economic regret resulting from the use of inaccurate design parameters obtained from using the selected model.

The work completed in this study has considered each of the above factors but only for a very limited sample of four Utah streams. Thus, it was not possible to formulate a very general model choice strategy based only on this study. In addition, economic regret will vary so much for different uses of generated sequences that it is not possible to include it in a generalized model choice strategy. Therefore, the proposed model choice strategy will consider only the first two factors and draws somewhat on the work of other researchers in order to broaden its applicability. To the extent that the proposed model choice strategy is based on work reported herein it assumes that preservation of $\rho(1)$ and K, and not the entire autocorrelation structure, is the goal of the analyst. A further limitation of the proposed strategy is that it does not take into consideration that preservation of K is of little importance in the design of a small reservoir (Hoshi, Burges, and Yamaoka 1978).

A model choice strategy was proposed for selection of a univariate annual stochastic streamflow model. The model choice is based on the $\rho(1)$ - K values estimated from the historic record and the feasible regions for each of the five models considered in this study. Figure 4.3 recommends an initial model choice for each $\rho(1)$ - K combination and covers the usual range of values for these persistence statistics. Where feasible regions for different models overlap, selection of the recommended model was based on the ranking with respect to the preservation of persistence statistics and the cost and ease of use.

Hoshi et al. (1978) showed that there was little advantage to using a long-term persistence model (i.e. ARMA, AMAK, FFGN, or BKL) if

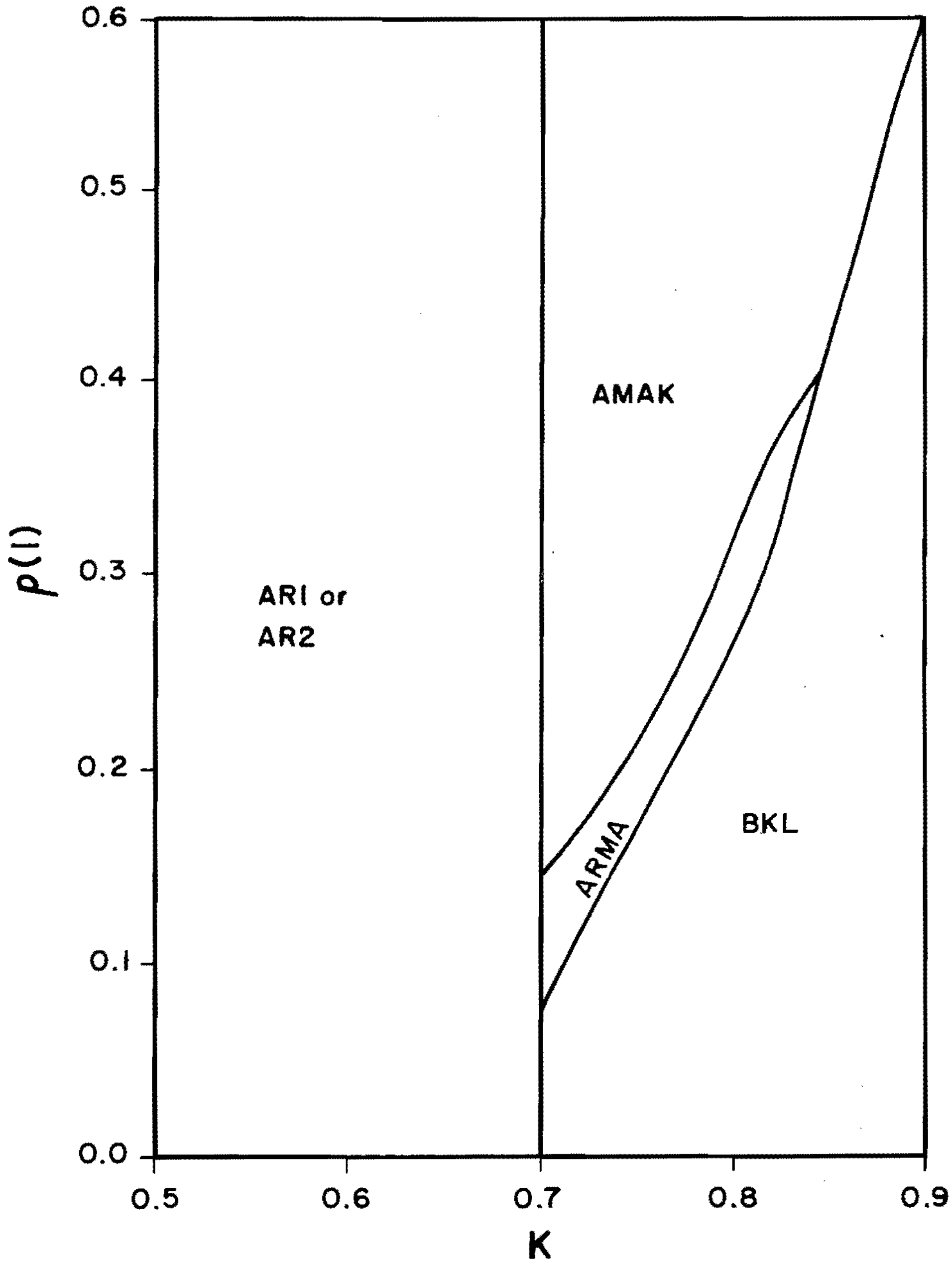

Figure 4.3. Recommended annual streamflow stochastic models based on ρ(1)-K values.

the value of K is less than 0.7. This result applies throughout the usual range of $\rho(1)$ values found in streamflows, that is $\rho(1)$ less than 0.6, and therefore the AR2 model is recommended for K less than 0.7 (see Figure 4.3). The feasible range of the FFGN model for K greater than 0.7 is completely covered by either the AMAK or ARMA models. Since these models are less expensive to run and were shown in this study to be more effective at preserving $\rho(1)$ and K than FFGN, the FFGN model is not included in Figure 4.3 as a recommended model. The AMAK model is recommended over the ARMA model because of its superior performance in preserving the persistence statistics. Since there are no other choices below the lower boundary of the ARMA feasible region the BKL model is recommended in that region.

Based on Figure 4.3 the AMAK model would be selected for all the study streams. Since the AMAK model is ranked first or second in Table 4.4 in all but one of the cases using the persistence statistics criteria, this would be an acceptable choice.

Conclusions

The following conclusions have been developed from the results and experience gained during this study:

1. The AMAK and ARMA models were judged best in terms of preserving the lag-one autocorrelation and Hurst coefficients, which are measures of the short and long term persistence of the streamflow sequence.

2. The BKL model is judged the overall best model in terms of minimizing the economic regret calculated in terms of the error in estimated agricultural benefits. However, the BKL model performed poorly with respect to preserving the persistence statistics and appears to have underestimated the design parameters, reservoir storage capacity and critical drought.

3. All five stochastic models generate average design parameters which are greater than the values based on the historic record. The AMAK and ARMA models consistently gave the largest values of the design parameters based on a 98 percent probability of nonexceedance.

4. The positive semidefinite property of the $\underline{BB}^T$ (or $\underline{EE}^T$) matrix for seasonal disaggregation model parameters was found to be sensitive to the transformation selected to remove skew from the historic streamflows, nonhomogeneities in the streamflow record, and the order m of $\underline{Z}_t$ for the MR model. It was found that a different choice m or a slightly changed starting year of historic record could change $\underline{BB}^T$ (or $\underline{EE}^T$) from negative to positive semidefinite.

5. A model choice strategy for selecting an annual stochastic streamflow model based on the values of $\rho(1)$ and K estimated from the historic streamflow record was proposed. This procedure does not necessarily select the best model for a particular stream but it does select one of the better models and will avoid the use of an unnecessarily complex model.

6. The James' parameter estimation procedure for the AMAK model led to parameter values which preserved the persistence statistics better than the Burges and Lettenmaier (1977) method.

7. Assigning the value of historic estimate of $\rho(1)$ to the lag-one autocorrelation coefficient of the high frequency component, $\rho^{(HF)}(1)$, of the FFGN model was found to give better preservation of $\rho(1)$ than the conventional procedure described by Chi et al. (1973).

Recommendations for Further Study

The following recommendations for further research are based on the experience gained during this study:

1. The alternative AMAK parameter estimation procedure used in the study should be compared with the procedure proposed by Burges and Lettenmaier (1977) to evaluate the effects of using each procedure on the design parameters.

2. The values of design parameters did not appear to be very sensitive to the model choice or the magnitudes of the persistence statistics for the four study streams. It is recommended that the sensitivity of these design parameters to a wide range $\rho(1)$ and K values be explored for each model. A sensitivity study of the effects of different values of the persistence statistics on the model regret should also be conducted. These sensitivity studies might provide information for improved model choice decisions near the boundaries of the feasible region where the choice is between a complicated or a simple model because it might be possible to predict the effects of preserving slightly changed values of the persistence statistics when a simpler model is selected.

REFERENCES

Box, G. E., and G. M. Jenkins. 1970. Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco, California. 533 p.

Burges, S. J., and D. P. Lettenmaier. 1975. Operational comparison of stochastic streamflow generation procedure. Technical Report No. 45, Harris Hydraulics Laboratory, Department of Civil Engineering, University of Washington, Seattle, Washington. 112 p.

Chi, M., E. Neal, and G. K. Young. 1973. Practical application of fractional Brownian motion and noise to synthetic hydrology. Water Resources Research 9(6):1523-1533.

Chow, V. T. 1951. A generalized formula for hydrologic frequency analysis. Trans. Am. Geophy. Union 32(2):231-237.

Curry, K., and R. L. Bras. 1978. Theory and applications of the multivariate broken line, disaggregation and monthly autoregressive streamflow generators to the Nile River. Technology Adaptation Program Report 78-5. Massachusetts Institute of Technology, Cambridge, Massachusetts. 416 p.

Gowon, D. T., J. C. Anderson, and B. Biswas. 1978. An economic interpretation of impact of phenologically timed irrigation on corn yield. Western Journal of Agricultural Economics. 145-156.

Griffin, Richard E. 1978. Personal communication.

Hanks, R. J. 1974. Model for predicting plant yield as influenced by water use. Agronomy Journal 65:660-665.

Hansen, R. D., H. H. Fullerton, A. B. Bishop, T. C. Hughes, R. K. Christensen, and D. S. Bowles. 1979. Historical and projected municipal and industrial water usage in Utah 1960/2020. Report UWRL/P-79-02. Utah Water Research Laboratory, Logan, Utah. 59 p.

Hoshi, K., S. J. Burges, and I. Yamaoka. 1978. Reservoir design capacities for various seasonal operational hydrology models. Proc. of Japan. Soc. Div. Engr. 273:121-134.

Hughes, Trevor C., and C. Earl Israelsen. 1978. Design criteria for rural domestic water systems. In: Drinking water supplies in rural American: An Interim Report. National Water Project, Washington, D.C.

Hughes, Trevor C., Clark Bigler, Jerry Olds, Richard Griffin, Arlo Richardson, L. Douglas James, Norris Stenquist, and James Harvey. 1978. Utah's 1977 drought. Report UWRL/P-78/07. Utah Water Research Laboratory, Logan, Utah. 49 p.

Hurst, H. E. 1951. Long-term storage capacity of reservoirs. Trans. Am. Soc. Civ. Engrs. 116:770-808.

James, R. W., D. S. Bowles, and N. T. Kottegoda. 1980. Model choice: An operational comparison of stochastic streamflow models for droughts. Draft Report, Utah Water Research Laboratory, Utah State University, Logan, Utah.

Jensen, D. T. 1978. Vulnerability of water supply systems to drought. Unpublished Ph.D. Dissertation, Department of Civil and Environmental Engineering, Utah State University, Logan, Utah. 179 p.

Jensen, D. T., and P. M. Ellis. 1979. Application of the Box-Jenkins forecasting methodology and Monte Carlo simulation to the generation of synthetic streamflows. Proceedings of the Third Conference on Hydrometeorology, American Meteorological Society Bogota, Colombia. pp. 101-105.

King, Charles V., Gerald S. Hatch, Harry E. Hughes, Robert D. Goff, and Stephen C. Downs. 1976. Water system evaluation and needs study: Monticello City. Coon, King and Knowlton Consulting Engineers. Salt Lake City, Utah.

Kottegoda, N. T. 1980. Personal communication.

Lettenmaier, D. P. and S. J. Burges. 1977. Operational assessment of hydrologic models of long-term persistence. Water Resources Research 13(1):113-124.

Magnuson, Marvin D. 1969. Meteorological drought in Utah: As expressed by the Palmer Index. Unpublished. U. S. Department of Commerce, ESSA, Weather Bureau, Western Region. Salt Lake City, Utah.

Mandelbrot, B. B. 1971. A fast fractional Gaussian noise generator. Water Resources Research 7(3):543-553.

McKee, Mac. 1978. Personal communication.

Mejia, J. M, I. Rodriguez-Iturbe, and D. R. Dawdy. 1972. 2-The broken line process as a potential model for hydrologic simulation: streamflow simulation. Water Resources Research 8(4):931-941.

Mejia, J. M., and J. Rousselle. 1976. Disaggregation models in hydrology revisited. Water Resources Research 12(2):185-186.

O'Connell, P. E. 1974. Stochastic modeling of long-term persistence in streamflow sequences. Doctoral thesis, Civil Engineering Department, Imperial College, London, England. 309 p.

Ogrosky, Harold O., and Victor Mockus. 1964. Hydrology of agricultural lands. In: Chow, Ven Te, ed. 1964. Handbook of Applied Hydrology. McGraw-Hill Book Co., New York.

Palmer, Wayne C. 1965. Meteorological drought. Research Paper No. 45. Office of Climatology. U. S. Weather Bureau. Washington, D. C.

Richardson, E. Arlo. 1971. Climate of Logan, Utah. In: Climatological Summary. No. 20-42. U. S. Department of Commerce, National Oceanic and Atmospheric Administration. Environmental Data Service. Washington, D. C.

Russell, Clifford S., David G. Arey, and Robert W. Kates. 1970. Drought and water supply: Implication of the Massachusetts experience for municipal planning. Resources for the Future. Johns Hopkins Press, Baltimore, Maryland.

Schmidt, Thomas A. 1975. A comparison of frequency distributions use to fit annual flood series. Unpublished Master of Science Thesis. Department of Civil and Environmental Engineering, College of Engineering, Utah State University, Logan, Utah.

U. S. Department of Agriculture. 1967. Irrigation water requirements. Technical Release No. 21, Revised September 1970. U. S. Department of Agriculture, Soil Conservation Service, Engineering Division, Washington, D. C.

Valencia, R. D., and J. C. Schaake. 1973. Disaggregation processes in stochastic hydrology. Water Resources Research 9(3):580-585.

Wallis, J. R., and N. C. Matalas. 1970. Small sample properties of H and K estimators of the Hurst coefficient h. Water Resources Research 6(6):1583-1594.

Yevjevich, V. 1972. Stochastic processes in hydrology. Water Resource Publications, Fort Collins, Colorado. 276 p.