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Rainwater Collection Systems: The Design of Single-Purpose
Reservoirs

by

Brian G. Latham

A thesis
presented to the School of Graduate Studies and Research
in partial fulfillment of the
requirements for the degree of
Master of Applied Science (Civil Engineering)
in
The Department of Civil Engineering

OTTAWA, Ontario, 1983

Brian G. Latham, 1983



Brian G. Latham, OTTAWA, Canada, 1983.

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ABSTRACT

The motivation for this thesis is the improvement of rainwater collection as a domestic water source. Hydrologic aspects and optimal sizing of the tank are its main foci, but an examination of the effects of major statistical parameters of rainfall on storage tank size is the main result.

Five methods previously used for the storage calculation are compared. From these, a family of models that simulate the actual operation of the reservoir was identified. These are models involving a simulation of the operation or behaviour of the reservoir.

A general computer model incorporating numerous calculation options was written. A new starting volume calculation was developed and shown to be superior to previous calculations.

A comparison of the storages calculated on a daily basis and a monthly basis was made and a method of approximating the daily values using monthly data was determined.

The monthly storage calculation was thoroughly tested using simplified data which indicated some of the characteristics of rainfall and their effects on storage.

A monthly rainfall time series model was developed. Parameters of the data model were varied and storages calculated using the principles of synthetic hydrology.

A major feature of the model is the non-dimensional nature of the calculations carried out.

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DEDICATION

To my mother,
who, in her wisdom, will not understand what
this whole thesis is about.

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Chapter I

INTRODUCTION AND NEED FOR THE THESIS

1.1 RAINWATER COLLECTORS AS A SOURCE OF WATER

The provision of safe water for human use and consumption is a major accomplishment of modern society. The methods used are all similar in that the natural hydrologic process is interrupted at some point, water is removed from it and is channelled through artificial devices to be cleaned, disinfected, used, and disposed of. To minimize costs and the danger of disease, great care is taken to obtain a source that provides the purest water available in sufficient quantities.

While surface and sub-surface waters are the most common source, under certain circumstances, the interruption of the hydrologic cycle by the collection, storage and use of rainwater is a viable, safe and economically sound option. A flow chart showing the relationship between conventional sources of water and rainwater collection is given in Figure 1.

The conditions that make a rainwater collection system viable may include:

1. no safe centralized water system is available.

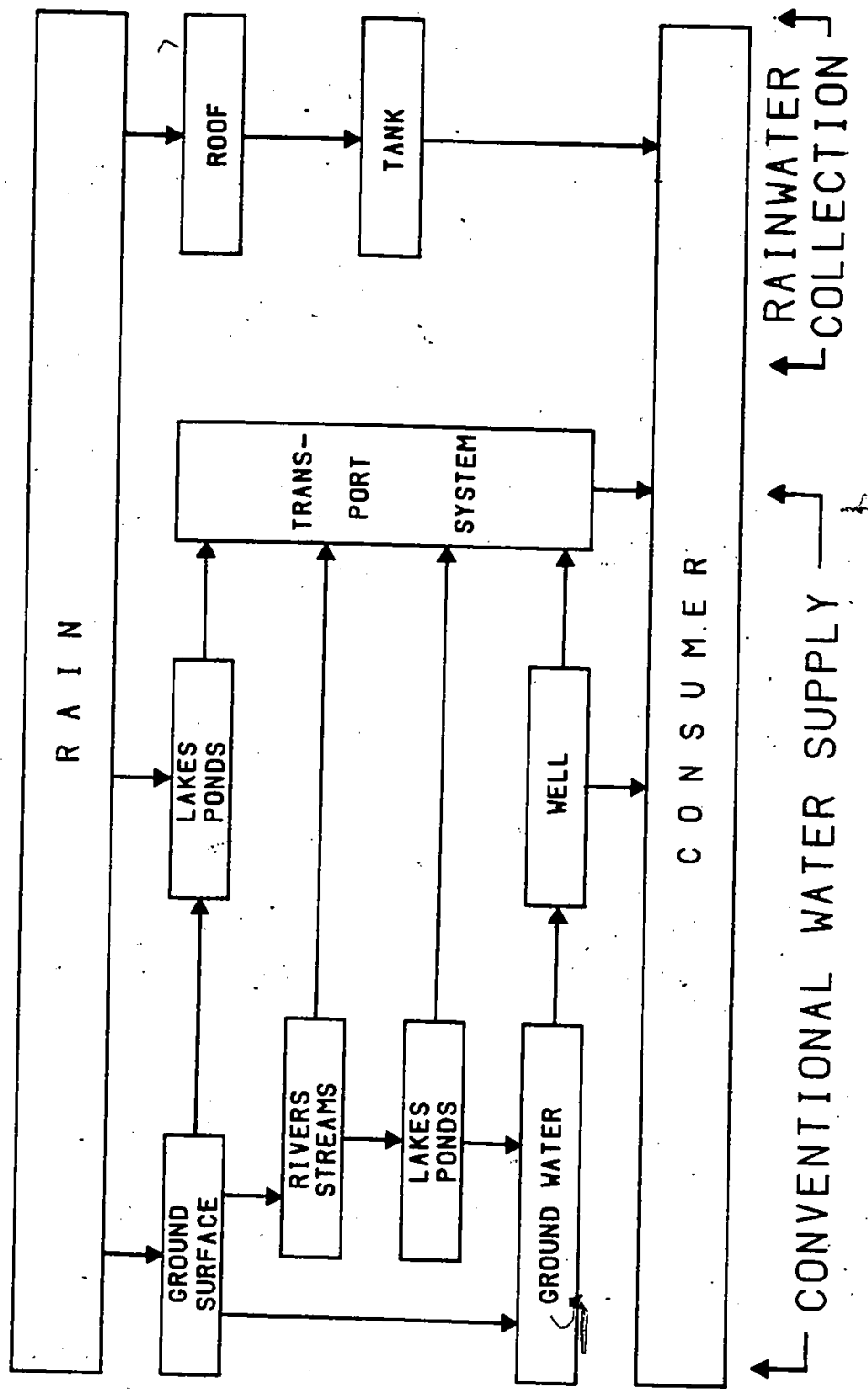


FIGURE 1: THE RELATION OF RAINWATER COLLECTION TO OTHER FORMS OF WATER SUPPLY

2. surface water supplies are unavailable, are of poor quality, or are available at a considerable distance.
3. wellwater is contaminated, chemically hard, difficult to obtain or unreliable.

Since the quantities of water available from a roof catchment system are small relative to modern demand levels, it may be necessary to complement the rainwater with water from other sources. Rainwater can be used for some purposes (eg. drinking and/or washing depending on the actual case) and the alternate source can satisfy other demands (eg. flushing). Alternatively, a mixed system combining the very pure rainfall with other water would give water with improved characteristics for all purposes.

Specific areas where rainwater does or may serve as a water source include:

1. Bermuda, Gibraltar and other islands where groundwater is contaminated by salt intrusion and/or runoff in streams is minimal [70], [67].
2. Australia with high evaporation rates, increasingly poor quality of river water, and large distances between individual consumers [26].
3. Nova Scotia where low water volume and high concentration of arsenic, iron and uranium in wells make well use expensive or impossible [75].
4. Pennsylvania and Ohio where strip mining works have lowered water tables and contaminated groundwater.

5. Eastern Ontario where contaminants (hardness, iron and sulphur) make wellwater in rural areas unsuitable for functions such as washing.
6. Southern Saskatchewan where wellwater is brackish and surface water is contaminated by algal growth in the summer.
7. suitable areas in less developed countries where poor sanitation causes surface supplies to be contaminated or where flooding and high water tables make safe sanitation impossible.

1.2 OUTLINE OF A RAINWATER COLLECTION SYSTEM

A typical system gathers rainwater, stores all or part of it until it is required and delivers it to the consumer. Additional features may be present to improve water quality. A schematic of the water flow in a system is in Figure 2 and an example household system is shown in Figure 3.

1.2.1 Collection

For most household users, the roof of a dwelling is used to collect the rain. Ground catchments may also be used but these are subject to greater contamination from animals, etc.

Water falling on the roof runs to the eaves and is carried away by gutters or a specially constructed feature in the roof. A downpipe conveys the water to the storage tank.

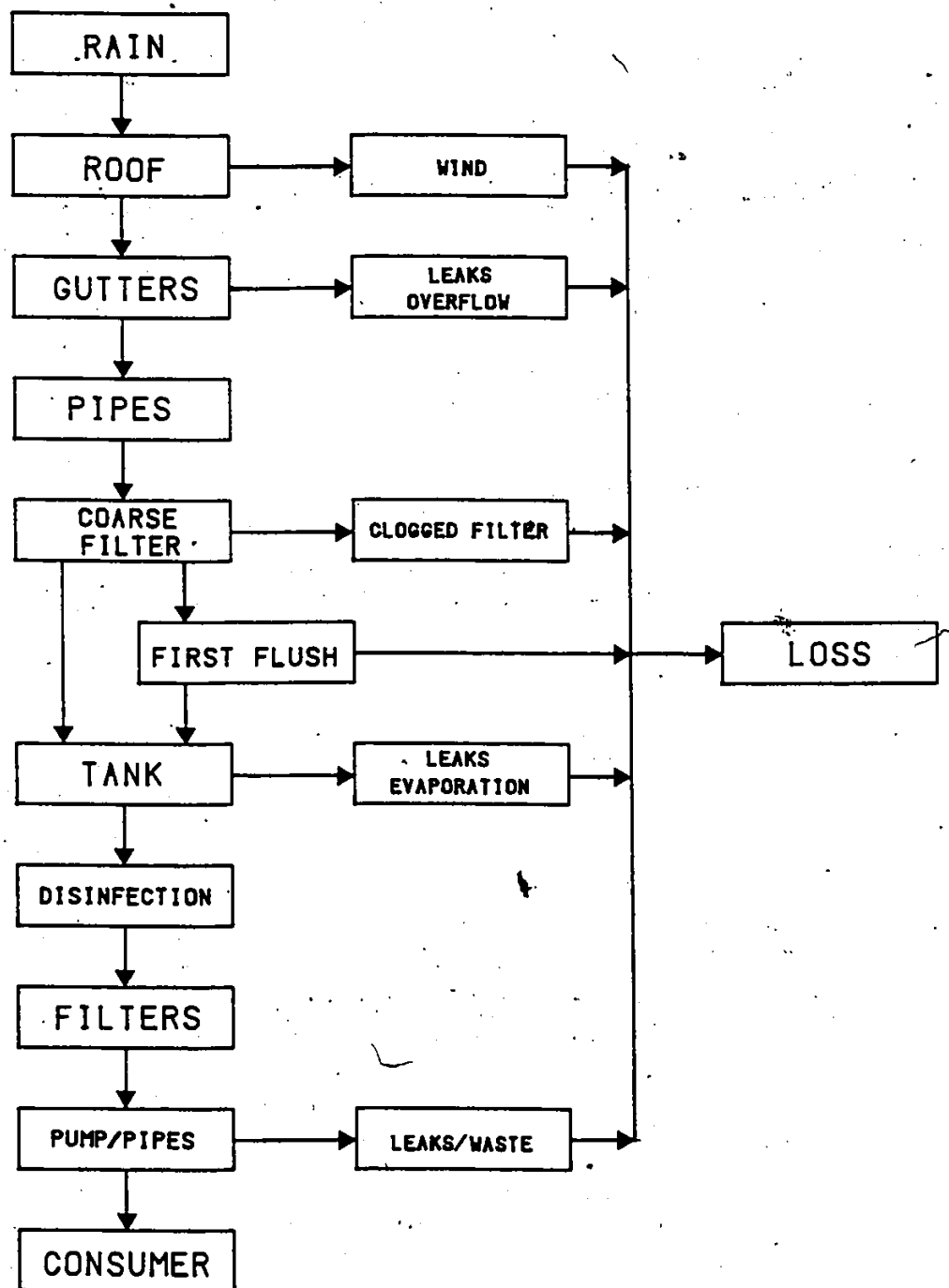


FIGURE 2: FLOW OF WATER IN A RAINWATER COLLECTOR

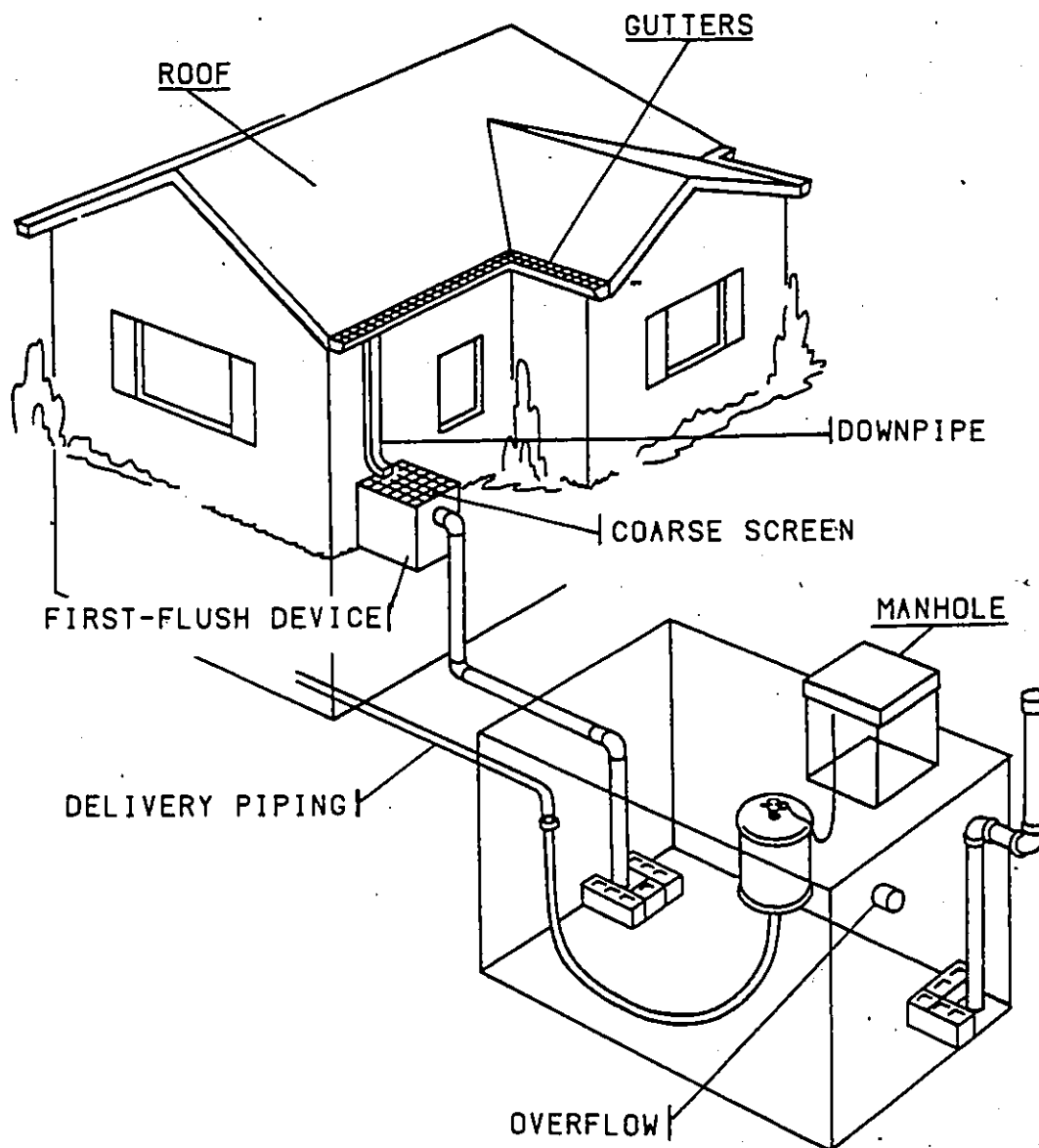


FIG. 3: A RAINWATER COLLECTION SYSTEM
(OHIO DEPT. OF HEALTH)

1.2.2 Storage

A covered impervious tank of sufficient size is an integral part of the system. It stores water during wet periods and releases it during low rainfall periods. It need not store all of the rain collected, only enough to make up the deficit between demand and inflow during low rain periods.

1.2.3 Delivery

Conventional pump or gravity systems can be used to deliver the water to the household as required. The quantities of water available are modest and a well-sealed and well-maintained system is advisable.

1.2.4 Water Quality Improvements

Water quality in a rainwater tank is usually good as storage itself allows dust and dirt to settle out and bacteria, if present, will die off in several days. However, water quality can be improved as well as tank cleaning delayed through the use of filters and a roof-flush device. The normal input filter is coarse to remove leaves, branches, etc. that are washed off the roof, but much finer filters can also be used. A subreservoir can be installed in the inlet line to collect the first water coming from the roof. This water, which has the greatest pollutant load due to the impurities picked up by the rain while falling and while running over the roof, is discarded when the rain is

over. Various types of devices are available. Filtering and disinfection of the water before use can also be practised and may be required by law.

1.3 DESIGN OF A RAINWATER COLLECTION SYSTEM

The data and calculations required for the design of a rainwater collection system include:

1. the collection area
2. the demand pattern
3. the rainfall pattern
4. the necessary storage volume.

The major area of uncertainty is in the rainfall regime, which must be analyzed in order to determine both the minimum collection area and the size of the tank.

The major constraint in the design process is cost. Individual water systems are relatively small structures compared to centralized urban systems and hence, it is not feasible to apply complex optimization models to determine the required combination of area and volume to meet the demand in a particular case. However, a tank that is either too small or too large represents a loss to the owner of service and money.

To properly design a tank requires a knowledge of the rainfall of the area where the collector is built. For even a simple analysis, considerable amounts of data must be obtained (a formidable and time-consuming task in itself)

and processed, usually in a computer or else by a hand calculator.

For most prospective collector owners, this is impossible or impractical since the cost of analysis may exceed the cost of the system or else a computer analysis may not even be available.

To overcome this, numerous attempts have been made to draw graphs that relate area, demand, rainfall and reliability ([26], [59], [31]) but they are confined to specific areas.

What is needed is a design curve that relates collection area, tank volume, rainfall characteristics and consumption rates. To keep costs down, the design curve should be easily obtainable from the available rainfall data.

The purpose of this thesis is to develop a simple method to construct a design curve.

The application of the hydrologic curves discussed in this thesis to an actual situation is discussed in Appendix A.

1.4 STATEMENT OF PROBLEM TO BE SOLVED

1. A flexible storage calculation model will be developed for use on computers to simulate the operation of a rain-water collector.

2. An attempt will be made to simulate rainfall and to relate rainfall characteristics to the storage required.

1.5 OUTLINE OF THESIS

In Chapter 2, a literature review is presented that covers the main topics of reservoir sizing methods, particularly those applied to rainwater tanks, the effect of input data parameters on calculated storage, and the choice of a model for monthly rainfall series generation.

In Chapter 3, the historic data to be used are examined in detail to show the minimum data required for a reasonable estimate of parameters and to examine the trend of the parameters over time. A preliminary comparison of five storage calculation methods is done and one of them is chosen.

Chapter 4 traces the development of the storage model giving the most flexibility in calculation and potentially, the largest storage values. This model involves a behaviour analysis. A detailed study of the effect of starting volume and the development of a new starting volume algorithm are done.

In Chapter 5, the model is thoroughly tested. A model-defining parameter and reliability parameter are tested on daily and monthly data and the monthly case is calibrated to the daily. Simplified data series are introduced into the calculation and the resultant storage patterns are noted.

In Chapter 6, a generation model for the data series is presented and found adequate. A comparison of the ability of four distributions used with the model to reproduce the data parameters and the storage required is done.

In Chapter 7, the rainfall generation model and the storage model are combined and the effects of various input parameters on the storage at two levels of demand are examined.

Chapter 8 contains a summary of the work done, a list of conclusions from it and notes on further work that might be undertaken in the same field.

1.6 RESTRAINTS

While building a computer model for the operation of a storage reservoir and building a statistical model to generate rainfall data to feed into it, it is well to remember that the computer simulation is only a two dimensional approximation to a multi-dimensional natural phenomenon.

No stochastic model can 'fill in' the missing data in a historical series, no stochastic model can guarantee that the optimum storage capacity it yields is the true optimum which one would arrive at if using the flow sequence that will actually materialize in the future. (p. 14 of [36])

A model only approximates nature. The solutions and answers obtained are only correct to the extent that the models reflect in some way the underlying physical reality.

However, modelling, while inherently imperfect, is an attempt to avoid possible mistakes in the future and to produce a best possible answer to a practical problem by extracting as much information as possible. Perfect knowledge is desirable but is in fact a metaphysical concept and

there is no shame in misjudging the future if all reasonable provision was made for it. No method is, in fact, infallible.

Finally, it is recognized by the author that the final decision about how large a tank should be built depends in large measure on the costs of construction. The ability of the owner to pay for the system will determine the level of service (reliability and demand levels).

The consideration of these costs is outside the scope of the present work. However, the hydrologic aspects of the system, as expressed in the demand/storage/reliability curves in this thesis are an important component of a complete analysis. The combination of physically possible systems and financially possible ones will result in a dependable and affordable water supply from rainwater collection. Grover [19] discusses the choice of a system based on physical and economic parameters while Heggen [23] has a more sophisticated economic model.

1.7 LIST OF TERMS AND SYMBOLS USED

1.7.1 Terms

Autocorrelation Function (ACF) - See 'Correlogramme'.

Behaviour Analysis - A computerized storage calculation method in which the inflow/outflow operation of a reservoir is simulated. There are many types, ranging from a conservative type (Yield After Spillage or YAS) where yield is calculated at the first of the period, inflow is added and spillage occurs before the yield is subtracted, to the liberal type (Yield Before Spillage or YBS) where yield is calculated and delivered after inflow is added but before spillage occurs.

Certainty - Probability in an EVI Distribution of storage values.

Coefficient of Skew (CS, γ) - A non-dimensional measure of skewness in data. See Appendix C.

Coefficient of Variation (CV) - A non-dimensional measure of variance in data. See Appendix C.

Conservative - Refers to storage calculations that produce large values of storage for a given demand. See 'Behaviour Analysis'.

Correlation - A measure of the tendency of high (low) values to occur at the same positions in two data series. In this thesis, the two series are obtained from the same data series but the values are offset by

a given number of lags. See Appendix C. See 'Lag'.

Serial Correlation (ρ_k) - An estimate of correlation at k lags using the complete data series.

Seasonal Serial Correlation $\rho(j)$ - An estimate at 1 lag of the correlation of data of season j with the data of the previous season.

Correlogramme - A plot of serial correlation vs. lag. Also called Autocorrelation Function.

Cyclicity - the change of data on a seasonal basis. Monthly Cyclicity refer to cycles of average monthly rainfall. Annual Cyclicity refers to changes in annual amounts from year to year.

Demand - The amount of water that a user requests from a reservoir in a year. It may be expressed as a volume (D), a depth of rain (D'), or as a non-dimensional fraction of mean annual inflow (D'' , Draft Ratio, Demand Fraction)

Demand Fraction (D'') - see 'Demand'.

Draft Ratio (D'') - See 'Demand'.

Economic Life - The lifetime of a structure over which the characteristics of the synthetic data are being studied. The length of the synthetic traces equals the structure's economic life.

Equilibrium - The state of a reservoir in which the operation is uninfluenced by the initial starting conditions.

Lag - The number of seasons that separate values for which a correlogramme is calculated.

Liberal - Refers to storage calculations that produce small values of storage for a given demand.

Markov Process - A series of data in which each value is in part determined as a fractional multiple of the immediately previous value.

Mass Curve - A graphical procedure used to determine the storage required for 100% reliability of supply. Due to Rippl [61].

Mean Annual Inflow (AR) - The average amount of rainwater collected each year. Calculated as collection area (A) times mean annual rain (R).

Partial Autocorrelation at lag k - the autocorrelation that is unexplained by a model with $k-1$ autoregressive terms. Its use comes from the resultant fact that if partial autocorrelation at lag k is zero (within some confidence level), the model of the data will have $k-1$ autoregressive terms.

Partial Autocorrelation Function (PACF) - a plot of partial autocorrelation against lag.

Precipitation - Total of rain and the water equivalent of snow.

Rain - Liquid Precipitation.

Rationing - Lessening of demand when the level in a reservoir is low.

Reliability - A measure of how much of the total demand is supplied by the system over the period of the data series being considered. May be time-based (number of time periods that demand is fully met as a fraction of the total number of periods) or volume - based (total volume supplied as a fraction of total volume demanded).

Return Period - The average elapsed time between occurrences of an event with a certain magnitude or greater (p.3 of [22]).

Risk - The probability that a value will be met or exceeded at least once in a given number of trials.

Runoff Coefficient - A number in the range [0,1] expressing the fraction of falling rain that is actually conveyed to the reservoir by the collection apparatus.

Season - The number of data periods into which a year is partitioned. One season means annual data, 12 seasons means monthly, 52 seasons means weekly and 366 seasons means daily, etc.

Seasonal Serial Correlation - See 'Correlation'.

Serial Correlation - See 'Correlation'.

Skew - A measure of the symmetry of the distribution of a data series. It may also be used to mean Coefficient of Skew. See Appendix C.

Snow - Solid Precipitation.

Spillage - The amount of inflow that is surplus to the capacity of a reservoir.

Stocking - The addition of water to a reservoir from a source other than rain falling on the collection area.

Storage - The minimum amount of water that must be stored in order to meet the demand on a reservoir at the required reliability. May be expressed as a volume (S), a depth of rain (S'), or as a fraction of mean annual inflow (S"; Storage Ratio, Storage Fraction).

Synthetic Hydrology - A process in which a number of supposedly statistically indistinguishable series are generated by computer. From these, a distribution of a statistic, eg. storage, can be ascertained.

Trace - One sequence of synthetic data of desired length.

1.7.2 Symbols

- a - scale parameter in EV1 distribution
- A - area of catchment surface
- A_j - location parameter for jth season in LN3 distribution
- ACF - autocorrelation function. See 'correlogramme'
- C - certainty (i.e. probability in EV1 distribution of storage)
- CS - coefficient of skew
- CV - coefficient of variation
- d'_i - demand in season i expressed as a depth of rain.
- D - yearly demand (volume)
- EV1 - extreme value I distribution (Gumbel)
- LG - like-Gamma distribution
- LN2 - lognormal 2-parameter distribution
- LN3 - lognormal 3-parameter distribution
- N - number of data points in a data series
- PACF - Partial Autocorrelation Function
- $q_{i,j}$ - ith generated flow value that is in the jth season
- q_x - non-logtransformed generated value
- q_y - logtransformed generated value
- r or r_i - rainfall depth in a season
- R - mean annual rainfall depth
- S - storage (volume)
- S' - storage (depth of rainfall) $S' = S/A$
- S" - storage fraction or storage ratio. $S'' = S'/R = S/AR$

t_i - normally distributed variate with mean 0.0 and variance 1.0. For use as part of the i th generated value.

$t_{i,j,\gamma}$ - transform of t_i from normal to LG distribution by the Wilson-Hilferty transformation using $\gamma_{t,j}$

T - return period

U - location parameter in EV1 (Gumbel) distribution

u_j - mean of values in season j

u_x - mean of non-logtransformed data

u_y - mean of logtransformed data as determined by the lognormal generation equations

Y'_i - yield in period i (depth of rain)

YAS - Yield After Spillage. See 'Behaviour Analysis'

YBS - Yield Before Spillage. See 'Behaviour Analysis'

γ_j - population CS for j th season

- γ_j transformed by consideration of serial correlation

γ_x - CS of non-logtransformed data

γ_y - CS used to generate logtransformed data

θ - behaviour analysis identification parameter. $\theta = 0$ means conservative or YAS, $\theta = 1$ means liberal or YBS

ρ_k - serial correlation at lag k

ρ_x - serial correlation of non-logtransformed data

ρ_y - serial correlation used to generate logtransformed data

$\rho(j)$ - lag one seasonal serial correlation between seasons j and $j-1$

σ - standard deviation

σ_j - standard deviation of values in the j th season

σ_x - standard deviation of non-logtransformed data

- σ_y - standard deviation used to generate logtransformed data
- ϕ_j - intermediate parameter in 2-parameter lognormal generation equation development
- ψ_j - intermediate parameter in 3-parameter lognormal generation equation development

Chapter II

LITERATURE REVIEW

2.1 RESERVOIR SIZING

A rainwater collector is a reservoir which receives stochastic inflows over time and is sized so as to maintain a minimum outflow rate.

The reservoir problem has been well-studied (Klemes, [39]). The basic problem is to analyse inflow data characteristics, given that the demand or release pattern is known and a certain level of system reliability is desired. The objective is to determine the smallest reservoir capacity necessary to maintain the output at the desired reliability. McMahon and Mein [47] reviewed the most common methods and classified them into two categories:

1. Critical period types which involve the analysis of inflow data (historical or synthetic) piece-by-piece to determine the period in the data series that is most severe (i.e. critical) and which defines the capacity. The best known method of this type in the English world is that of Rippl [61] (see p. 134-137 of [39]).
2. Moran type methods in which inflow series characteristics are used to construct matrices that show the

probability of a reservoir's beginning a time period at one specified volume and finishing it at another. The reservoir is subdivided into a number of discrete possible volumes or states. These matrices are then multiplied by themselves until a steady-state transformation matrix results. Although Moran [49], [50] is credited by many with developing this technique, Klemes (p. 82 of [39]) reports earlier work in Russian by Savarenskiy and, Kritskiy and Menkel. The methods of sizing rainwater tanks considered in this thesis are all of the first type.

2.2 RAINWATER TANK SIZING

In studying rainfall for Stillwater, Okla., Ree et al. [59] used a method of Jeppson [32] which incorporated features from Waitt and Alexander (see pp. 36-38 of [47]) which was an attempt to assign a probability of occurrence to storage values determined by the Rippl mass-curve technique used on historical data.

Grover [19] used a Rippl analysis on historical data in Kenya to determine storage.

Perrens [53] and Hoey [25] in Australia, Satijn [65] in Indonesia, Pearson et al. [51] and Jenkins et al. [31] in California applied what McMahon and Mein (p. 24 of [47]) called a behaviour analysis. The use of this terminology is followed in this thesis, although the term "behaviour" for

this particular calculation technique is imprecise. Any method attempts to predict the future behaviour of the reservoir under unforeseen conditions. The particular meaning it has in this case is the simulation of actual mass flow of the reservoir on a computer. Rainfall data are processed through the algorithm in sequence. Various additional factors such as rationing by users in times of low volume (i.e. drought) [52], evaporation [52], [65], leakage [65] and availability of outside water sources in time of drought [52] can be added to the basic calculation. Jenkins et al. [31] identified two possible models of this type: a Yield After Spillage (YAS) or conservative model and; a Yield Before Spillage (YBS) or liberal model. The model eventually used in this thesis is of the YAS behavioural type. A more complete discussion of the model is given in Chapter IV. McMahon, Codner and Joy [46] list its advantages as:

1. simplicity.
2. ease of display of time sequence of water content.
3. uses data directly. Therefore distribution type, seasonality and time dependence are automatically taken into account.

Simpler approximate methods are also available. Jenkins et al. (pp. 30 and 55 of [31]) suggested that a Rippl mass curve analysis on the mean monthly values augmented by 50% would be adequate.

A more detailed description of these methods and a numerical comparison of them are presented in Chapter III.

For design purposes, nomographs or curves were produced by most researchers. Hoey [25] produced graphs for South Australia. Ree et al. [59] produced a nomograph for their area. Jenkins et al. [31] regionalized the analysis for 13 areas in California by producing an envelope curve and from this a nomograph. All of these design procedures may work well in their areas but the analysis is regional and the specific design aids have little application outside of those areas.

Many papers readily available to the public have been based on quite simple analyses. Wentworth [77] produced a pamphlet for the Hawaii Water Authority in which he examined the return period for low rainfalls of various durations but he gives only rough guidelines for calculation of the amount of storage required. A Peace Corps manual [74] and an Environmental Protection Agency (USA) book [13] simplistically calculate the volume needed as a function of the number of days between rainy periods.

2.3 REPRESENTATION

As outlined by Klemes (p. 83 of [39]), the operation of the system can be summarized in a plot of demand, storage and reliability. The usual method is to plot demand as a fraction of mean inflow vs. storage as a fraction of mean

inflow for different values of reliability. Mean annual inflow in this case is area times mean annual rainfall. Jenkins et al. [31] plotted these on a log-log scale.

This representation has the advantages of being

1. compact. The long columns of figures in Schiller and Latham [66] can be compared with the plots of the same information in Chapter III.
2. non-dimensional. For the designer, there is no need to worry about metric or American units.
3. useful in design. One point on the curve represents many combinations of demand, area, and storage.
- .. 4. suitable for curve-fitting and development of formulae.

2.4 RAINFALL PARAMETERS AND THEIR EFFECT ON STORAGE

The storage required for a rainwater collection system depends on the characteristics of the inflow. A wide range of possible theoretical factors has been considered by researchers. Of particular note is Phatarford [57] who, in a clear theoretical article, derives conclusions by mathematical analysis. He used a single-season, Gamma-distributed Markov sequence.

2.4.1 Means

Phatarford [57] found that increasing mean annual inflow decreases required storage. Jenkins et al. (p. 38-39 of [31]) found the monthly means as a proportion of mean annual rainfall (mean seasonal distribution) accounted for considerable amounts of the required storage. Perrens (p. 109 of [54]) refers to previous use of mean annual rainfall as an indicator of storage in Australia.

2.4.2 Variability

Jenkins et al. (p. 39 of [31]) cite storage theory to show that

$$S'' = \frac{\pi}{\sqrt{24}} (CV) N^{0.5} \quad (2.1)$$

where S'' is mean storage required as a fraction of mean annual rainfall, CV is coefficient of variation of rainfall, N is the number of years of record. This implies that greater variability about seasonal means increases the required storage. Phatarford [57] showed that increasing annual inflow variance increases required storage and that a 10% increase in mean annual inflow has a greater effect than a 10% reduction in annual standard deviation. Perrens (p. 113 of [54]) notes from several Australian rainwater storage curves that less seasonal and annual variation implies less storage required. Burges and Linsley [4] found that for normally distributed annual series with a correlation of 0.2

the storage increases 148% as the CV increases from 0.25 to 0.5. Fair, Geyer and Okun (p. 7-2 of [14]) state that CV of annual rainfalls in North America varies from 0.1 for "well-watered" regions to 0.5 for arid regions. They state "high values of CV signify high storage requirements."

2.4.3 Skew

Phatarford [57] found that increasing annual inflow skewness decreases required storage, a 10% reduction in annual standard deviation produces a greater effect than a 10% increase in the annual coefficient of skew and, the effect of annual skew is appreciable for demands less than 90% of mean annual inflow.

Phatarford gives no reason for these results other than their being products of the model chosen. However, they may be due to the assumption of a gamma-distributed inflow. As skew increases in this distribution, the variance and the effective range (to some probability level) decrease (p. 101 of [22]). The effect of this is to cause milder fluctuations from year to year and thus decrease the storage required.

2.4.4 Serial Correlation or Persistence

Seasonal serial correlation is the tendency for high (low) seasonal values to follow high (low) preceeding values in a time series.

Jenkins et al. [31] concluded from storage calculations on synthetic records that storage is not strongly dependent on lag-one seasonal correlation. Compared to uncorrelated data, the storage was 5% higher for correlation of 0.1 and 10% higher for 0.2. The average correlation of 13 California stations was 0.07.

Perrens and Howell [56] generated normally distributed, serially correlated flows and concluded that as serial correlation increases, the storage required increases or reliability decreases. Burges (p. 80 of [3]) and Burges and Linsley [4] used an annual normal Markov model to show that storage required for series with annual correlation of 0.2 and 0.4 was 25% and 54% above that for uncorrelated data. Phatarford [57] showed that increasing annual inflow serial correlation increases required storage.

Although no reasons for this effect are given by the researchers, the reason may be that increased correlation represents a decrease in information in the data. A correlated data value contains some information derived from its predecessors as well as new information. The higher the correlation, the less new information contained in a series of a given length and thus the less certain (within given confidence limits) is any statistic derived from the data. Increasing the correlation is equivalent to shortening the data series. Storage calculated from highly correlated data is based on less new information than that calculated from

weakly correlated data and thus tends to be higher to maintain the same reliability. A discussion of the decrease of information content with increased autocorrelation is given in [44].

2.4.5 Critical Period

The required storage is usually determined by a particular period of the data. This is called the critical period. McLeod and Hipel [45] define it as the period between successive full storages that has the least accumulated inflow. Storage will increase with the severity of the critical period deficit. Fok et al. [18] illustrate the idea for rainwater collectors on a weekly basis. McMahon and Mein [47] consider it suitable only for preliminary design.

2.4.6 Other Factors

2.4.6.1 Sums of Mean Monthly Rainfall

Irish et al. [28] did successive linear correlations with storage required for rainfall in Indonesia. In order of decreasing coefficient of determination, the important parameters were:

1. sum of mean monthly rainfall for 5 driest consecutive months
2. mean annual rainfall
3. as for 1. but 3 months,

4. as for 1. but 4 months,
5. as for 1. but 6 months,

2.5 SIMULATION OF RAINFALL SERIES

2.5.1 Review

A particular series of historical rainfall data reflects the processes operating at a single site but it is only one realization of those processes. Only one storage value can be assigned to it. It is not possible to determine with what probability that storage value occurred, but it is almost certain that the rainfall series itself will not occur again. In other words, there is a basic problem in designing for the future using only the rainfall series of the immediate past. To try to overcome this, attempts have been made to reproduce different series of data that are statistically indistinguishable from the historical series and hence are probable outcomes of the same physical process. With sufficient numbers of series or traces, the probability of given storage values can be determined (assuming, of course, that the processes are not going to change in the future and that the model accurately reflects the process). This technique is called synthetic or operational hydrology and it has grown out of the storage estimation problem. It has the disadvantage of being no more accurate than the estimation of the model parameters, which is usually done from historical records and hence may be

unrepresentative of the future (see Klemes [38]). While many researchers have contributed to the field, the work culminated in that of the Harvard Water Resources Group [71] on simulation of streamflow records. Many of the methods are grounded only in statistics and hence may be applied to any suitable time series. This statistical approach is questioned by some who feel that the models should better mimic the actual physical process [36]. Phenomenological models of rainfall are reviewed by Waymire and Gupta [76].

Phatarford [57] sees simulation as an engineering method. He lists its drawbacks as:

1. models are usually chosen for ease of data generation and may not always fit the historical data well,
2. the final result (eg. storage size) is very much subject to sampling errors,
3. the computational effort required is enormous.

The rationale for these methods is given in many works [15], [17], [29]. The last gives a history and summary of some more common models and sets down criteria for a generation model (p. 60). It should

1. mirror nature in all those aspects that have been identified as important,
2. be minimal with respect to this parameter set (parsimony condition),
3. provide an easy means of adjusting the parameters of interest,

4. have parameters that can be obtained in some reasonable way,
5. produce results that agree with historical data and/or phenomenological considerations.

Phatarford (p. 202 of [57]) lists 4 necessary model properties:

1. the stationary distribution should be of the gamma type (an assumption based on streamflow literature),
2. parameters preserved should be mean, variance, coefficient of skew and serial correlation,
3. it should be analytically tractable,
4. it should be such that data can be generated from it.

2.5.2 Monthly vs Daily Data

Rainwater collectors are used on a daily basis and for accurate calculation of storage, daily rainfall should be used. However, there are numerous difficulties with daily data. These are:

1. the computational difficulties in handling daily data.
2. difficulties in obtaining daily data. Daily data are not easily available but monthly are [8], [72], [73].
3. synthesis of daily data is difficult because there are many parameters required and they are not easily determined.

There is an error in using monthly rather than daily data for calculation of required storage and corrections must be made for this. No consideration of this problem or a rational method to correct it was found in the literature reviewed.

2.5.2.1 Rainfall Models

Most precipitation models in recent literature reproduce series with a time increment of one day or less. Court [10] mentioned only daily models and Waymire and Gupta [76] specifically omitted monthly models in their review. Very few works have considered the case of monthly rainfall.

The models for daily or more frequent rainfall involve two parts

1. modelling whether or not rainfall occurs in an interval
2. if it does, modelling the depth.

Cole and Sherriff [9] reviewed previous models and used a Markov sequence for occurrence as did Richardson [60], Jackson [30], Heggen [23], Katz [34], and Haan et al [21]. Chin [6] studied the validity of the Markov chain for occurrence prediction. Roldan and Woolhiser [63] compared first-order Markov chains and an alternating renewal process with separate distributions for wet and dry interval lengths.

Daily rainfall amounts were obtained from an exponential distribution [60], a combination of uniform and exponential [21], and historical histograms [9]. Distributions were compared by Roldan and Woolhiser [64].

Other approaches have been taken. Adamowski and Smith [1] produced a lag-one Markov daily model which was only slightly more accurate than a random model. Sieker [68] made extensive use of white-noise models for single rainfall events.

For monthly series, Jenkins et al. [31] fitted a single-season monthly statistical (Thomas-Fiering) model with a normal distribution. It was not clear how seasonality was included in the model. Leytham [42] transformed each month's data to a lognormal 3-parameter distribution and generated data with a white noise, normally-distributed Thomas-Fiering type model. Leytham and Franz [41] studied monthly rainfall, finding lag-1 correlations small (less than 0.2) and, in general, less than for streamflows. In addition, multilag correlations were insignificant. Skew and CV were higher than for streamflows. They concluded (p. 28):

It appears that the correlation structure of monthly rainfall data in general fits that implied by a Markov model much better than does streamflow data.

In the same vein, Rodriguez-Iturbe and Mejia (p. 714 of [62]) state:

The temporal structure of rainfall in terms of years, months or weeks appears to be quite weak

and the first autocorrelation coefficient is practically always less than 0.2.

Delleur and others [11], [12] modelled the square roots of monthly rainfall in Indiana, Illinois and Kentucky. After normalisation using monthly means and standard deviations, the data were fitted to several models including ARMA(1,1) and ARMA(0,0) (white noise). The first passed all goodness-of-fit tests while the second passed half of them. Since all models fitted gave forecasts that followed each other and tended to the mean of the square roots, the white noise model was deemed equivalent to other models and easier to apply in practice.

2.5.3 Model: Monthly Thomas-Fiering

Like Leytham and Franz [41] and McMahon and Mein (p. 158 of [47]), the model chosen is the Thomas-Fiering lag-one Markov model, (see Chapter VI) which is amply discussed in Fiering and Jackson [17] with some corrections and in Kite and Pentland [35]. Basically, it relates normalized data in successive seasons. Theoretically, on a statistical basis, it will produce data with given seasonal means, variances and lag-one correlations and with a distribution similar to that from which the random portion is taken.

The Thomas-Fiering Model has often been used for generation purposes. It may not be as good at reproducing the precise rainfall values in one given series as more complex models combining various transformations of the data and the

fitting of ARIMA (autoregressive, independent, moving average) models. However, in this case, it is of more practical use because the objective is the investigation of the effects of rainfall series parameters on storage rather than the reproduction of the particular data series. The parameters of the Thomas-Fiering model can be directly related to the data and are easily interpreted and altered, as well as satisfying the criteria in section 2.5.1. It is for these reasons that it is used here.

2.5.4 Distribution

Four basic distributions are used with Thomas-Fiering: normal, log-normal 2-parameter, log-normal 3-parameter and like-Gamma (LG), i.e. the Wilson-Hilferty transformation (see p. 126 of [47]). The choice of the distribution depends on the degree to which the data parameters and the required storage are reproduced. On this, Leytham and Franz (p. 22 of [41]) say

Historic records are usually so short that arguments about the distribution are inconclusive.

Fiering et al. [16] take an operational approach in saying

It is evidence of statistical immaturity to argue whether the flows at a particular site are distributed normally, log-normally or like gamma if the subsequent design decision is not materially affected.

In light of the high skews of rainfall, a 3-parameter model (LN3 or LG) might be expected to give better results.

Joy and McMahon [33] found that a skewed, seasonal lag-one model was needed to preserve mean, standard deviation and storage. However, Burges (p. 130 of [3]) used a LN2 because he felt that skew was difficult to estimate due to short-record lengths. He said that skew could not be reliably estimated with fewer than 140 points and was meaningless with under 50.

2.5.5 Application of Model

McMahon and Mein (p. 114-7 of [47]) outline the procedures to follow in applying a model and Stedinger and Taylor [69] provide an example of the process for several models. A major consideration is the length of the trace. This should correspond to the economic life of the structure. Burges [3] used a life of 40 years as it was the lowest value for major structures. He based a study of the number of traces required to calculate storage on this level.

Burges [3] thoroughly examined the storage calculated using a 'sequent-peak' algorithm (similar to Rippl) for data generated with a Thomas-Fiering LN2 model. He concluded:

1.

The monthly studies showed conclusively that a large number of simulated storage values is needed to accurately determine the distribution of storage particularly at the higher levels of demand. (p. 118)

and

For the monthly generators 500 traces are adequate (for the 40-year economic life tested) for a fairly uniform runoff pattern

under heavy demand while a larger number, say 1000 traces, are needed for the highly concentrated, highly correlated runoff pattern... (p. 127)

The number depends on variability of values, inter-month correlations and demand.

2. Reliability depends very much on the initial storage value chosen for the storage algorithm.
3. The distribution of the required storage is extreme value 1 (also called Gumbel's extreme value distribution). Storages from traces longer than 40 years conform better to the EV1 distribution than those shorter than 40 years.
4. Demand patterns are critical to storage requirements. Time dependent demand schedules should be used.
5. Due to short streamflow records, use of skew is futile.

Chapter III

HYDROLOGY, DATA AND PRELIMINARY EXPERIMENTS

3.1 THE SIZING OF A RESERVOIR TANK

The amount of water entering a rainwater collector is the product of the collection area, A , and the rainfall depth for a given period, r .

Over the long run, the average amount coming into the system per year (or mean annual inflow) is area, A , times mean annual rainfall, R . Long-term annual demand cannot be greater than $A \times R$ without failures. The alternatives to failure are to reduce demand or to increase inflow by increasing the area. Demand/ AR is called the draft ratio or demand fraction. In practice, economics usually dictates that the demand fraction be much less than 100%. A guide that some design books use is to set the demand fraction at no more than minimum annual inflow as determined from data divided by mean annual inflow.

This is somewhat simplistic. The true case requires calculating the relationship between demand and storage in relation to the rainfall data. It will later be shown that most demands can be met if a sufficiently large storage is built. However, for demand above the minimum annual inflow, proportionately larger storage is needed.

3.2 HYDROLOGY

3.2.1 Runoff Coefficient

For a rainwater collector, the routing is fairly straightforward. Rain falls on a roof or other collection area, is conveyed by the roof to the gutters and from there to the downpipes and the tank. Due to the extremely small area, there is no catchment storage or appreciable time delay.

There are collection losses due to evaporation, overflowing gutters, wind and so on. These can be handled by subtracting a set amount during each time period or by using a runoff factor. Perrens [52] subtracted 2 mm per month. Hoey and West [26] found a runoff coefficient of 0.8. Ree [58] found that the windward side of a metal roof delivered 96% of the rainfall and the leeward 89%. The EPA [13] suggests that the losses depend on roof type: up to 15% for shingle or tar and gravel; 0 for sheet metal. Thomas [70] uses a runoff coefficient of 0.75 for limed, concreted roofs in Bermuda.

3.2.2 Snow and Cold

Cold weather presents considerable problems for rainwater collectors. Severe cold, such as in Canada, may cause the collection apparatus to cease operation as gutters and pipes are frozen solid. Many users disconnect pipes to prevent damage. Wind may blow snow off roofs. Ree [58] found that only 50% of snow was collected.

A complete model of the effects of winter would involve data for temperature, solar radiation, etc. Such a model is outside the scope of this thesis. However, as a first approximation for this study, only rainfall data supplied by Environment Canada were used. The presence of snow was taken to mean that systems were too cold to be able to collect water. The inclusion of winter rain, which might not actually be collected due to frozen apparatus, was assumed to compensate for snow that did melt. No direct studies were carried out to verify this.

3.3 HISTORICAL DATA USED: OTTAWA CDA

The historical data used in this thesis are for Ottawa CDA (The Experimental Farm) station 6105976, which is situated presently at 45°, 22', 58" N and 75°, 42', 54" W and is operated by the Atmospheric Environment Service of Environment Canada. Records for rain, snow and precipitation were obtained on magnetic tape as daily readings from the Climatological Archives. The data began in November, 1889 and ended December, 1981 inclusive.

3.3.1 Anomalies

A check on the reliability of recording of the data was made. The possible anomalies in AES data are [2]:

C - precipitation occurred, amount uncertain, value is

0.

E - estimated

F - accumulated and estimated

L - precipitation may or may not have occurred, value is 0.

A - accumulated amount, previous value C or L

M - missing

T - trace, value is 0.

Only 13 readings were missing. They were snow data for April 5, 6, 7, 8, 17, 20, 21, 23, 24, 26, 27, 29, 30 all in 1951. There was a total of 39 anomalies of less importance than "missing". If it is assumed that snowfall readings are taken for an average of 6 months per year, there are about 50,000 records represented (precipitation is not counted). Therefore, total anomalies were only 0.1% and missing values were only 0.025%.

Because the percentage of errors was so low and missing data were snow data, the following repairs were deemed satisfactory:

1. missing data were set to 0.
2. for C, L, no change made, i.e. value = 0.
3. for A, no change in value
4. for E, F, estimates accepted
5. for T, traces taken to be 0.

3.3.2 Rainfall Data Characteristics

From this data, only the rainfall values were used for the reservoir algorithm. The daily values were accumulated into monthly values and random checks were made on the calculations by comparison with published AES monthly data. They agreed within 0.1 (cm for snow, mm for rain and precipitation).

3.3.2.1 Summary of Statistics

A summary of statistics for Ottawa CDA rainfall is given in Table 1.

3.3.2.2 Means

To show the effect of neglecting snow, a plot of monthly averages of total precipitation and of rain was made. This is shown in Figure 4. It can be seen that, while precipitation is reasonably well-distributed throughout the year, consideration of only rain gives a wet/dry pattern.

3.3.2.3 Variation and Skew

Plots of seasonal coefficients of variation and coefficients of skew are in Figure 5. Coefficient of variation appears to be related to mean monthly values. For monthly means above the overall monthly mean (0.0833), coefficient of variation is about 0.5, but for months below the mean, it is 1.0. There is no discernible pattern in the coefficients of skew.

TABLE 1

Statistics of Ottawa CDA Rainfall 1890-1981

STATISTIC	MONTHLY	ANNUAL
Length of Record	1104	92
Mean Rain (mm):	55.4	664.4
Min Rain (mm):	0.0	398.8
Min Monthly/Mean Rain:	0.0	0.0
Min Ann/Mean Rain:	7.20	0.600
Max Rain (mm):	250.2	910.8
Max Monthly/Mean Rain:	4.52	0.377
Max Ann/Mean Rain:	16.45	1.37
Variance (mm ²):	1622	10820
Std. Dev'n. (mm):	40.3	104.0
Coeff. of Variation:	0.728	0.157
Skew (mm ³):	52800	276000
Co. of Skew	0.808	0.245
Correlation		
Lag 1	0.376	0.089
Lag 2	0.204	0.044
Lag 3	-0.023	0.027

3.3.2.4 Serial Correlation

Serial correlations estimated from the whole data set are plotted in Figure 6. Seasonal serial correlations (i.e. February's correlated with January's, etc.) are plotted in Figure 7. Plots of correlation have confidence limits. The formula for these limits was determined by Andersen for a random normal time series (see p. 109 of [47] and p. 93 of [3]) to be:

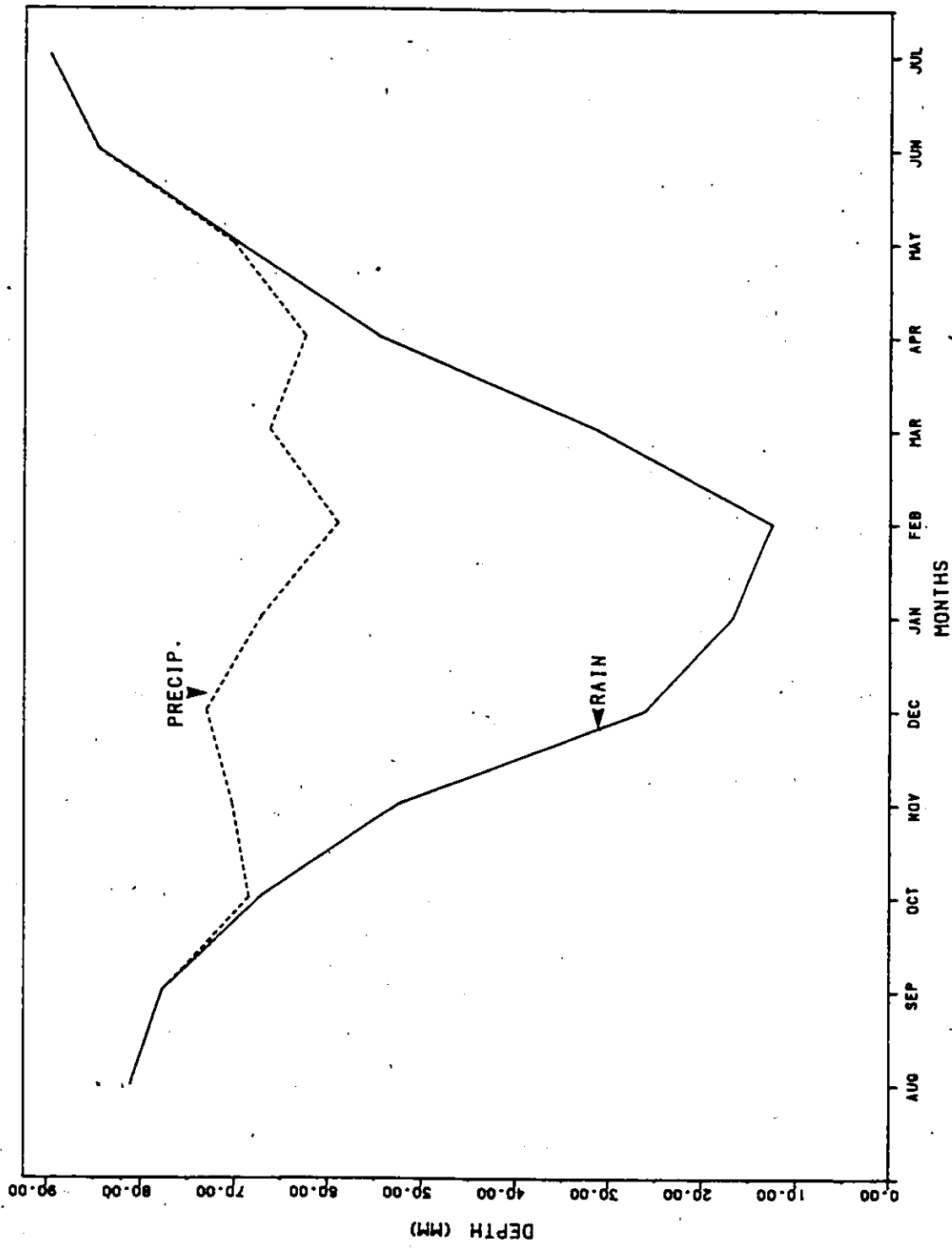


FIGURE 4: MEAN MONTHLY PRECIPITATION AND RAIN, OTTAWA CDA, 1890-1981

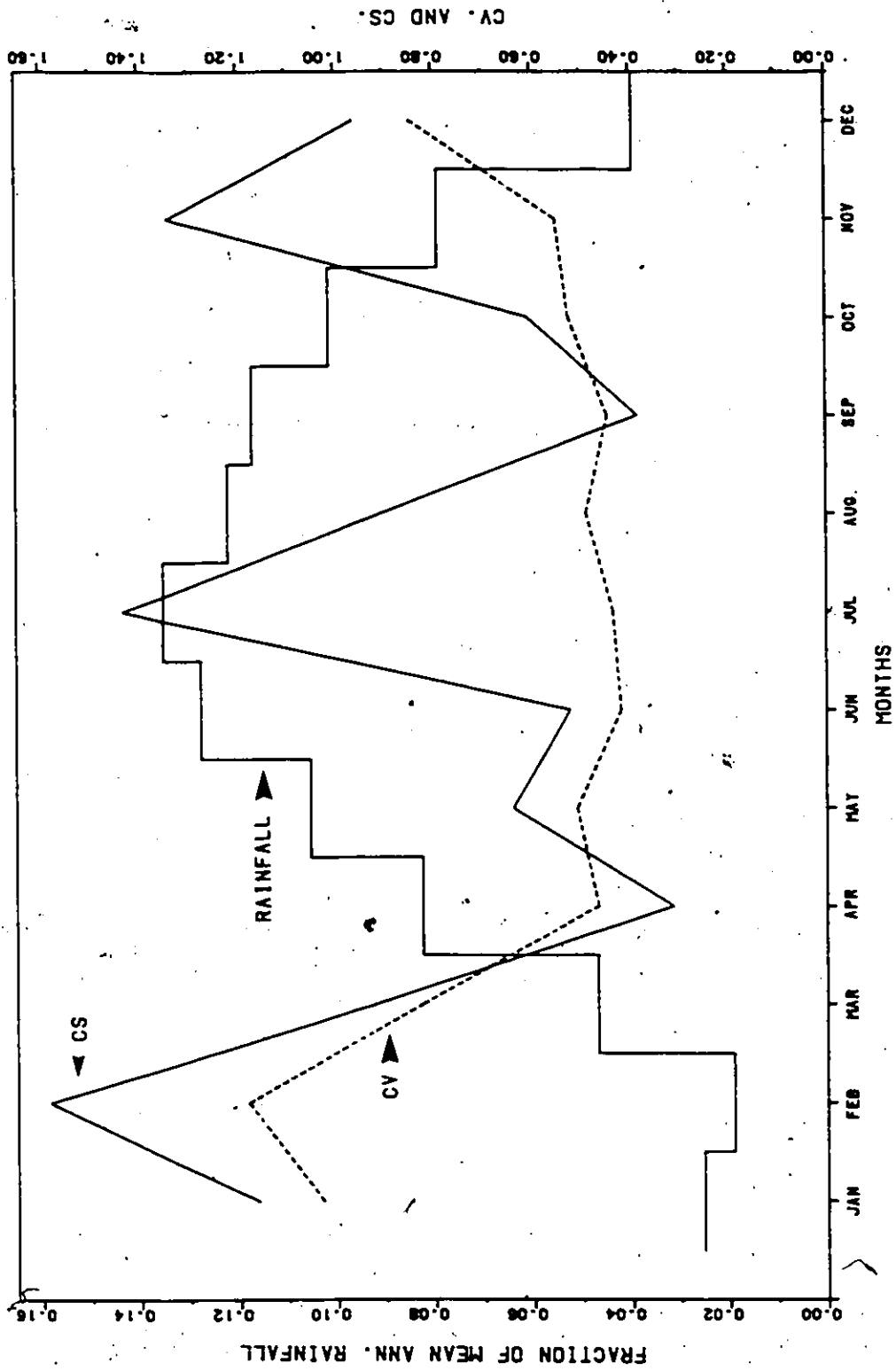


FIGURE 5: MONTHLY MEAN FRACTIONS, CV AND CS, OTTAWA CDA, 1890-1981

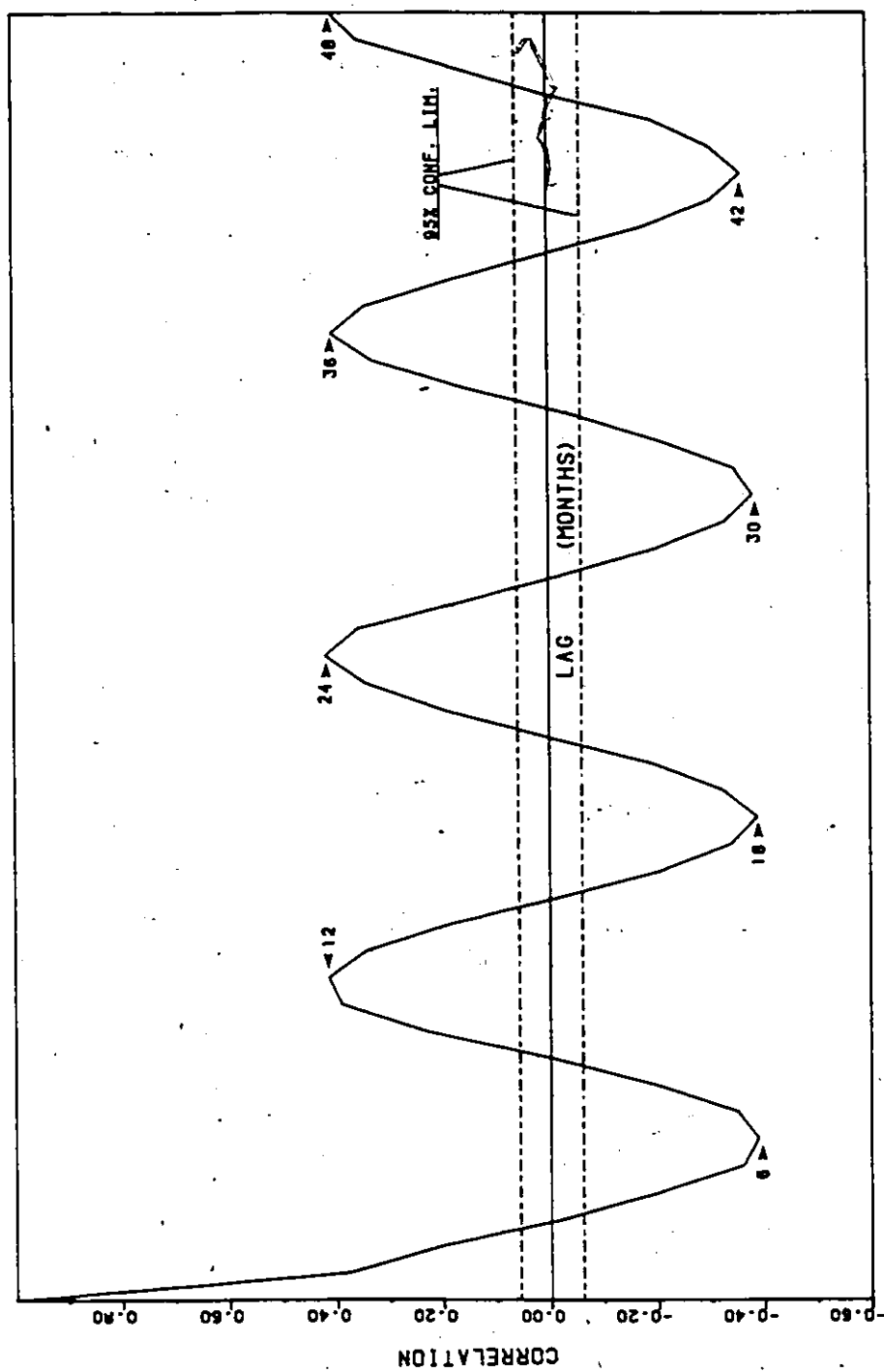


FIGURE 6: AUTOCORRELATIONS OF MONTHLY RAINFALL, OTTAWA CDA, 1890-1981

$$CL(\rho_k) = \frac{-1 \pm Z_{\alpha} \sqrt{N-k-1}}{N-k} \quad (3.1)$$

where Z_{α} is the standard normal deviate at the level of significance

N is the number of data points

k is the number of lags.

For the 95% level the limits are listed in Table 2.

TABLE 2

Confidence Limits for Serial Correlation

lag	---- Amount of Data--	
	1104	92
1	(-.060, .058)	(-.215, .193)
2	(-.060, .058)	(-.217, .194)
3	(-.060, .058)	(-.218, .195)

The plots show that, while many serial correlations are significant, the lag one seasonal correlations are not significantly different from zero at the 95% level. In a separate investigation, it was found that the correlations of annual rain data for lags 1, 2, 3 are also not significantly different from zero.

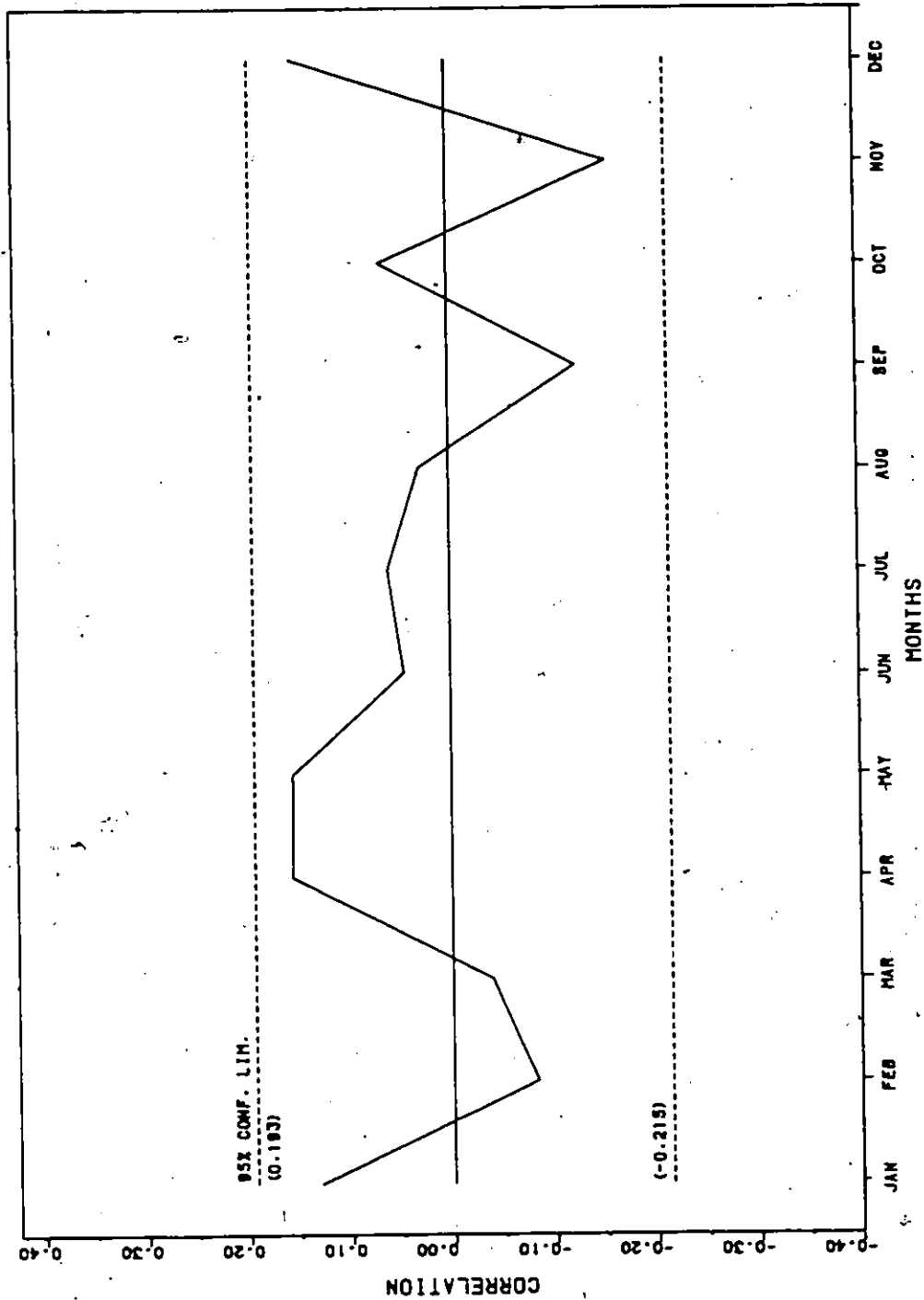


FIGURE 7: LAG-1 SEASONAL SERIAL CORRELATIONS, OTTAWA CDA, 1890-1981

3.3.3 Parameter Estimation from Data

To examine how much data is required to estimate different statistical parameters, and thus to obtain a qualitative estimate of how reliable are their values, the data were carefully examined. First, progressive estimates of a number of parameters were made with 1 to 92 years data. The data were treated in annual blocks with the parameters being estimated using all of the data up to that time. Forty-year moving estimates of the monthly parameters were also made in order to show the long-range trends in the data. The values were expressed as a fraction of the long term (92 year) value. In these estimates, the monthly values were calculated for all months together and were not specific to particular seasons. Annual estimates were calculated from values for 12-month periods summed together.

3.3.3.1 Mean

Monthly and annual mean are equivalent and are estimated well with relatively short data as shown in Figure 8. Forty-year estimates of monthly mean plotted in Figure 9 show a slight increasing trend but the values are only $\pm 8\%$ from the long term value.

3.3.3.2 Variance, Coefficient of Variance

Progressive estimates in Figure 10 and 11 show that monthly values of variance and coefficient of variance

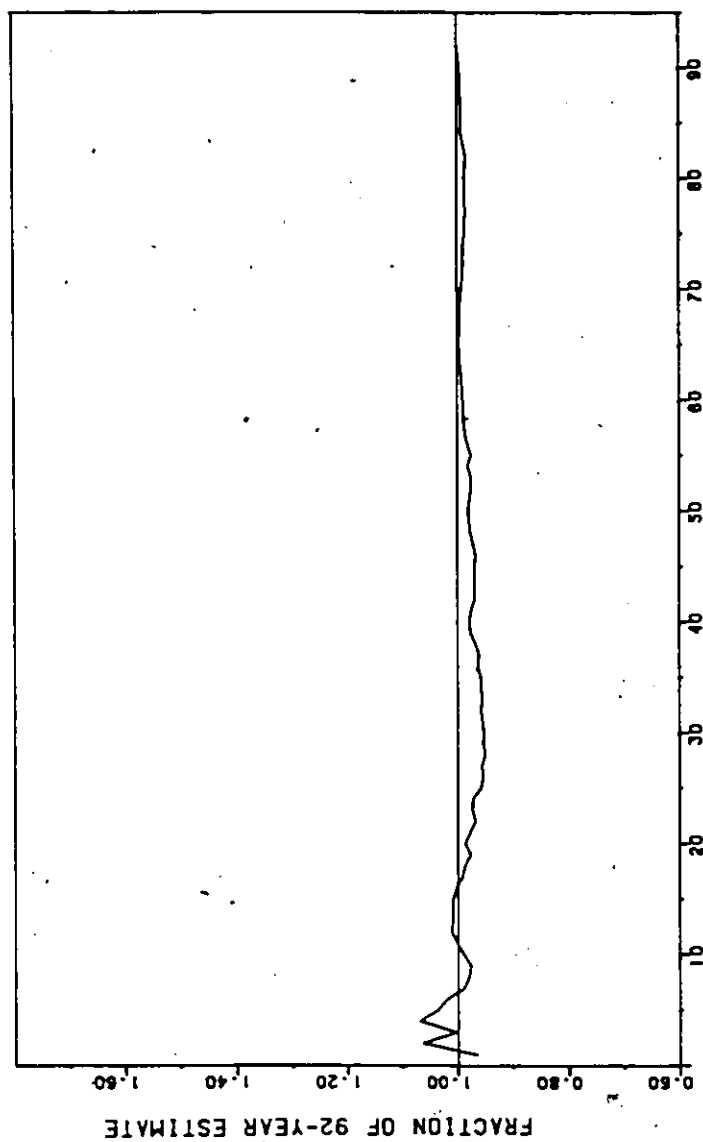


FIG. 8: PROGRESSIVE ESTIMATES OF ANNUAL MEANS.
OTTAWA CDA. RAIN. 1890-1981.

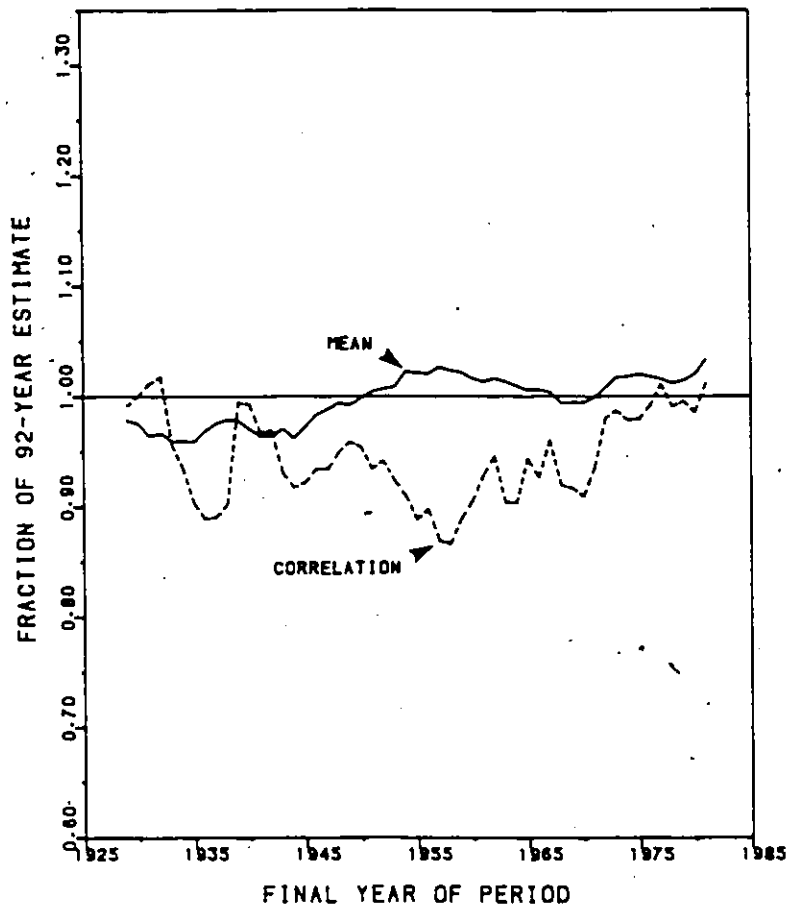


FIG. 9: 40-YEAR ESTIMATES OF MONTHLY MEAN
AND LAG-1 CORRELATION
OTTAWA CDA. RAIN. 1890-1981.

decrease with the length of the series, but are within 10% with 25 years of data. CV is subject to less variation than variance. Similarly, the progressive estimates show that annual variance is subject to great sweeps depending on the length of estimation period but these are not as severe for annual CV.

Forty-year estimates in Figure 12 show monthly variance and CV to be decreasing in time since 1890. Variance varies from 1496 to 1770, i.e. $\pm 9\%$ of the 92-year estimate, but coefficient of variance varies from 0.7793 to 0.6950, $\pm 7\%$. Monthly CV has been decreasing with time since 1890.

3.3.3.3 Correlation

The progressive estimates in Figure 13 show that the lag-1 monthly correlation estimated by 10 or more years of data is within 5% of the longterm estimate. The 40-year period estimates in Figure 9 show that correlation values vary depending on the period chosen for estimate. Forty-year period estimates ranged from 0.326 to 0.383 and were generally below the 92-year estimate of 0.376.

The annual correlation coefficient (lag-1) was much more erratic, changing sign and magnitude repeatedly, as would be expected of a low-significance value.

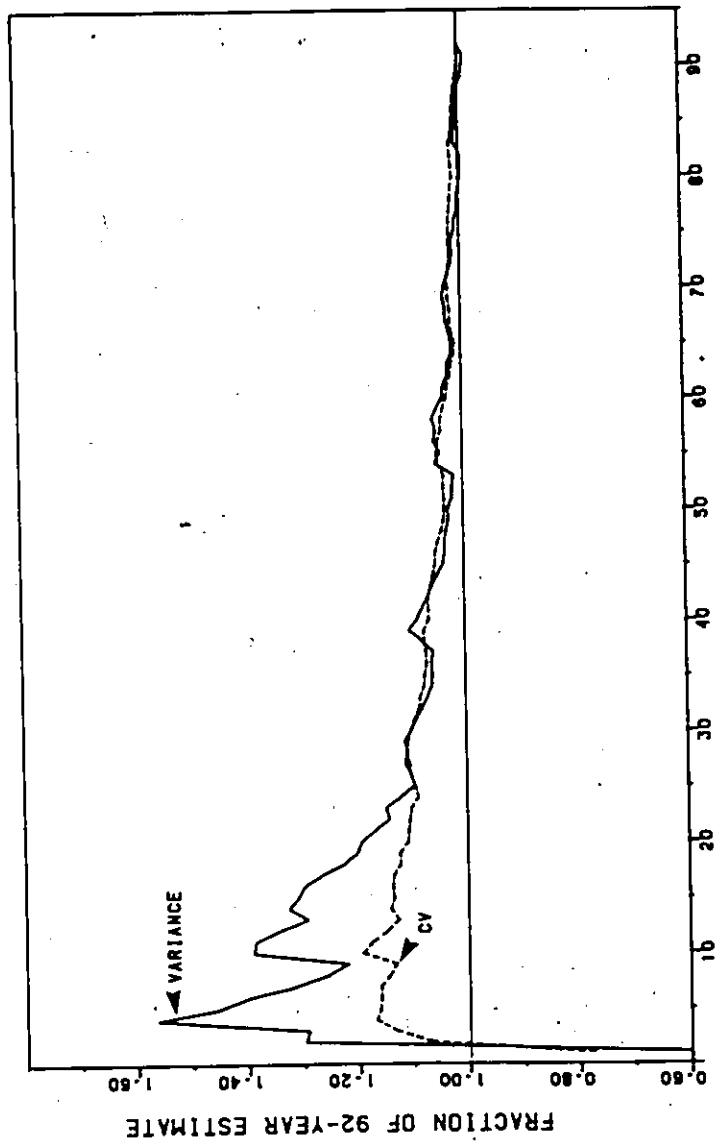


FIG. 10: PROGRESSIVE ESTIMATES OF MONTHLY VARIANCE AND CV.
OTTAWA CDA. RAIN. 1890-1981.

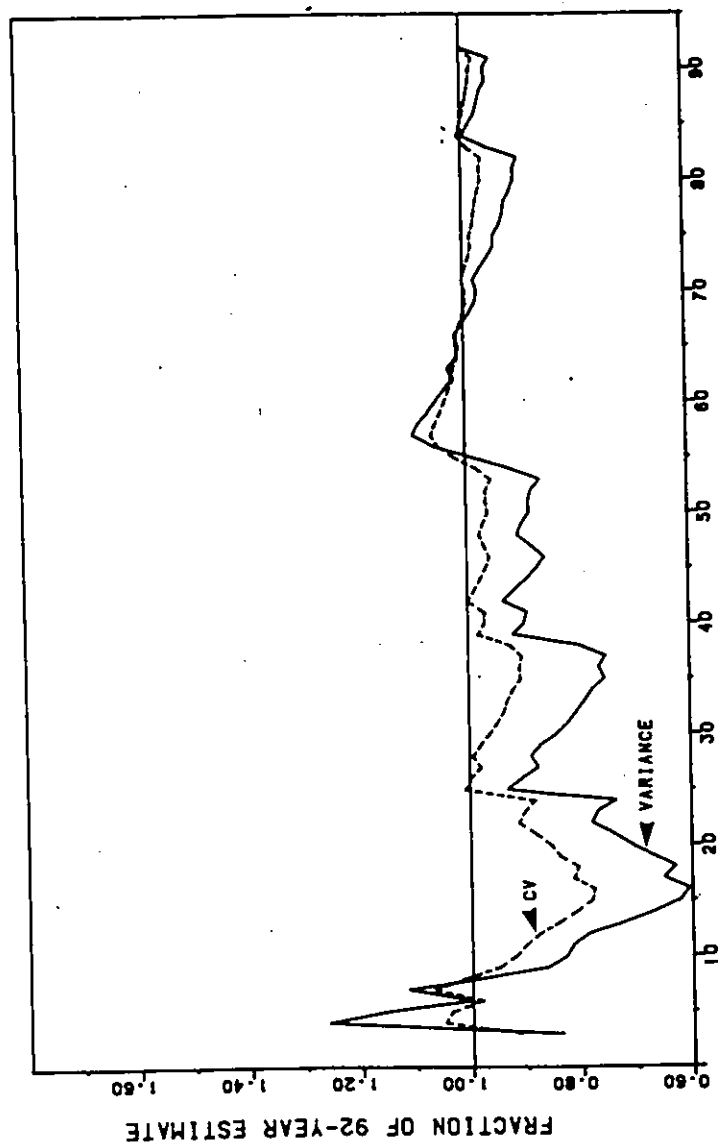


FIG. 11: PROGRESSIVE ESTIMATES OF ANNUAL VARIANCE AND CV.
OTTAWA CDA, RAIN, 1890-1981.

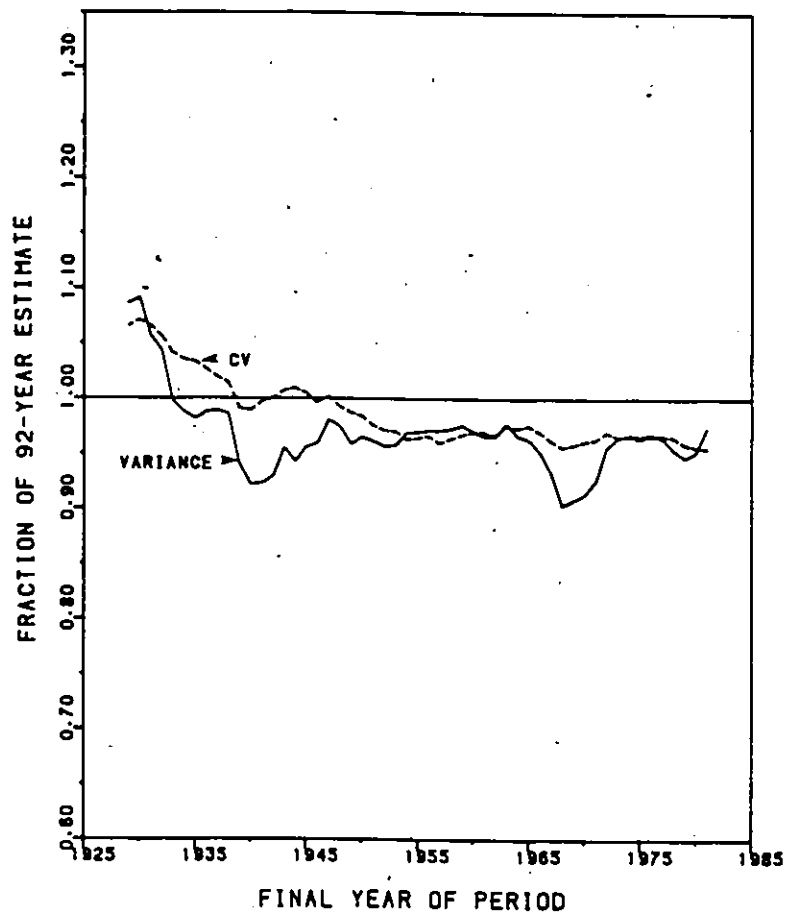


FIG. 12: 40-YEAR ESTIMATES OF MONTHLY VARIANCE AND CV.
OTTAWA CDA. RAIN. 1890-1981.

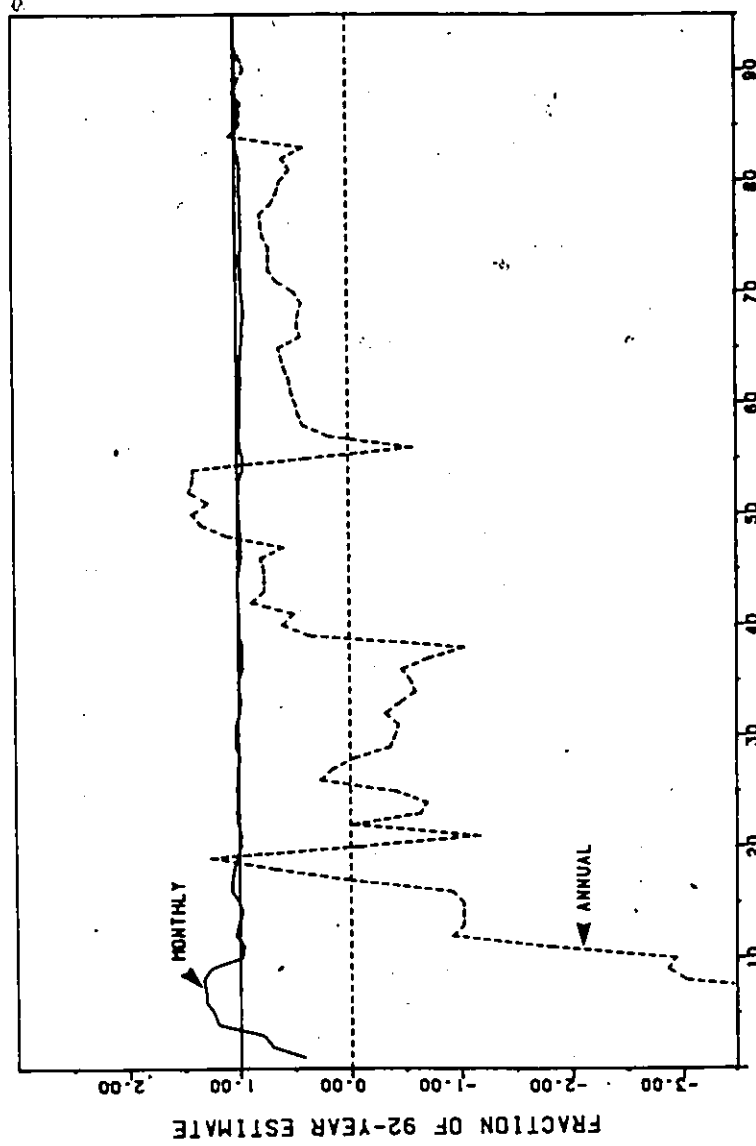


FIG. 13: PROGRESSIVE ESTIMATES OF MONTHLY AND ANNUAL LAG-1 CORR.
OTTAWA CDA. RAIN. 1890-1981.

3.3.3.4 Skew

As shown in Figures 14 and 15, monthly skew generally decreases with increased data while annual skew fluctuates considerably. Monthly CS forty-year estimates in Figure 16 show that its value has been decreasing in time since 1890.

3.3.3.5 Discussion

The estimates of most annual parameters differ more than 10% from the longterm estimates. This may be due to the small population size for estimation of these parameters. Although not calculated here, individual monthly means, variances, skews and correlations are expected to have similar estimation problems. Monthly parameters estimated from the whole dataset are much better estimated. However, monthly parameters are not constant in time. The monthly mean, for example, shows a slight increasing trend. Because of this, the statistics calculated from the data will vary depending on the period of estimation taken. Thus, the most recent data of sufficient length to estimate the desired statistic should be used in any analysis.

In this data, 40 years of data appear to give reliable parameter estimates. Thus, 40 years or more of the most recent data should be used for estimation purposes.

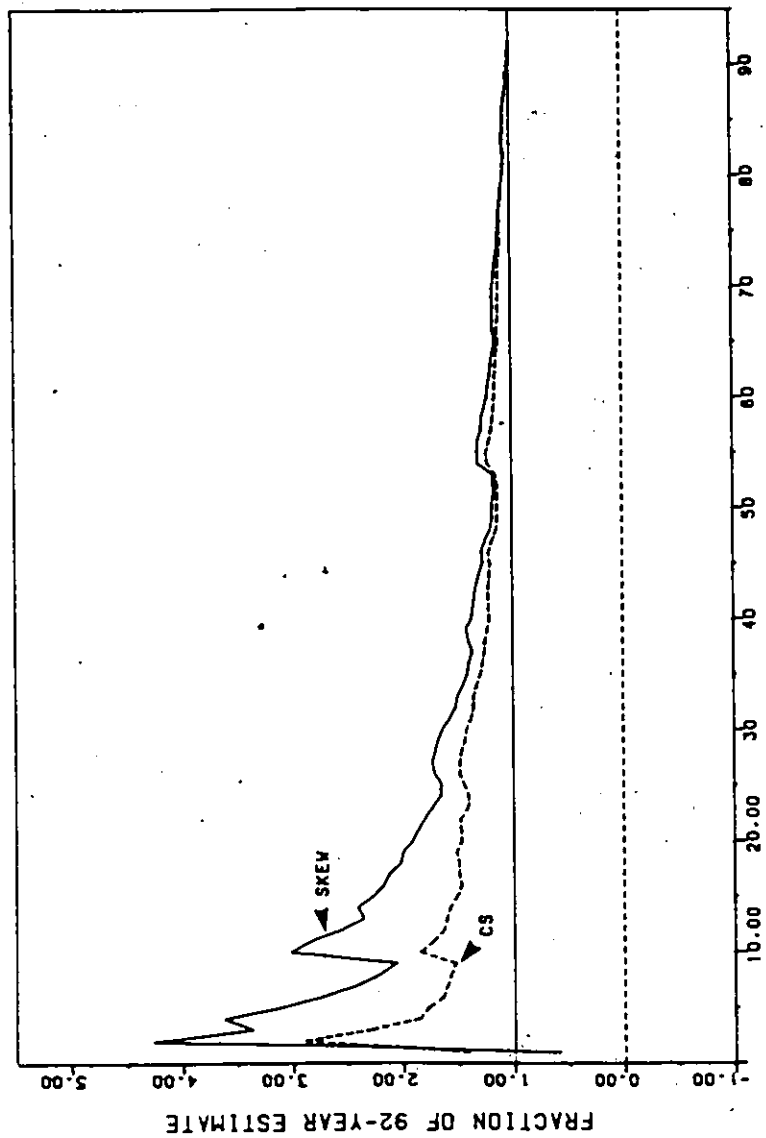


FIG. 14: PROGRESSIVE ESTIMATES OF MONTHLY SKEW AND CS.
OTTAWA CDA, RAIN, 1890-1981.

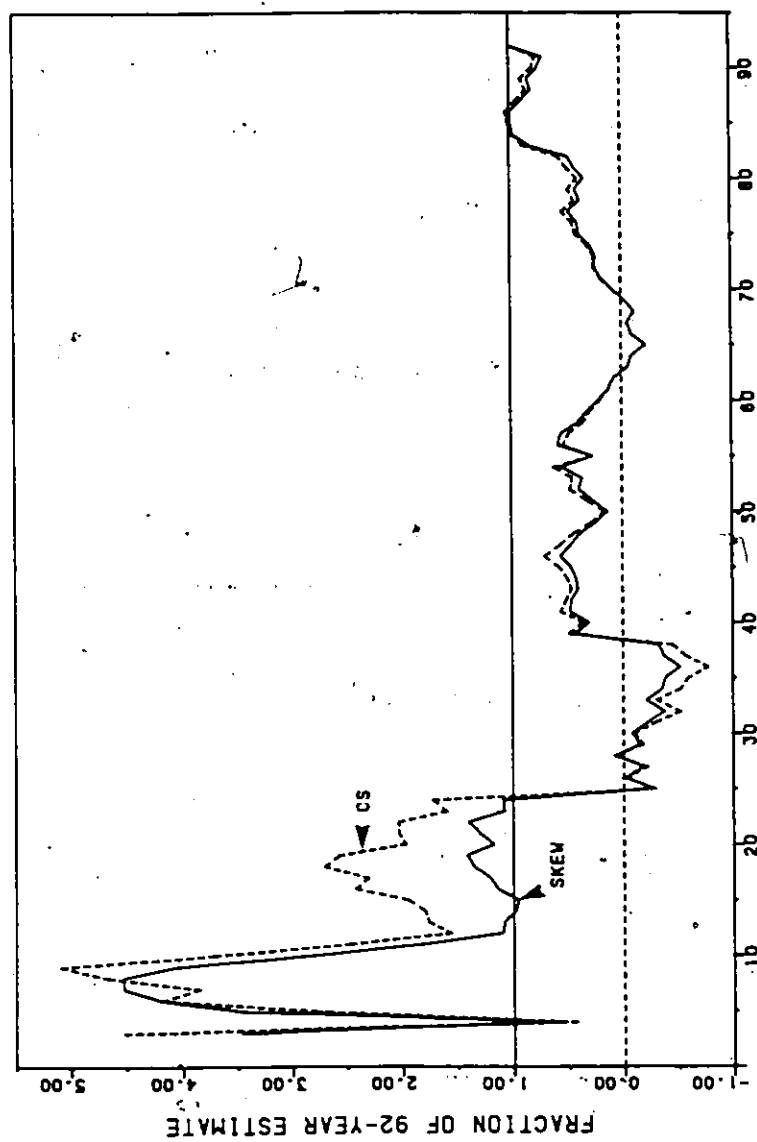


FIG. 15: PROGRESSIVE ESTIMATES OF ANNUAL SKEW AND CS.
OTTAWA CDA. RAIN. 1890-1981.

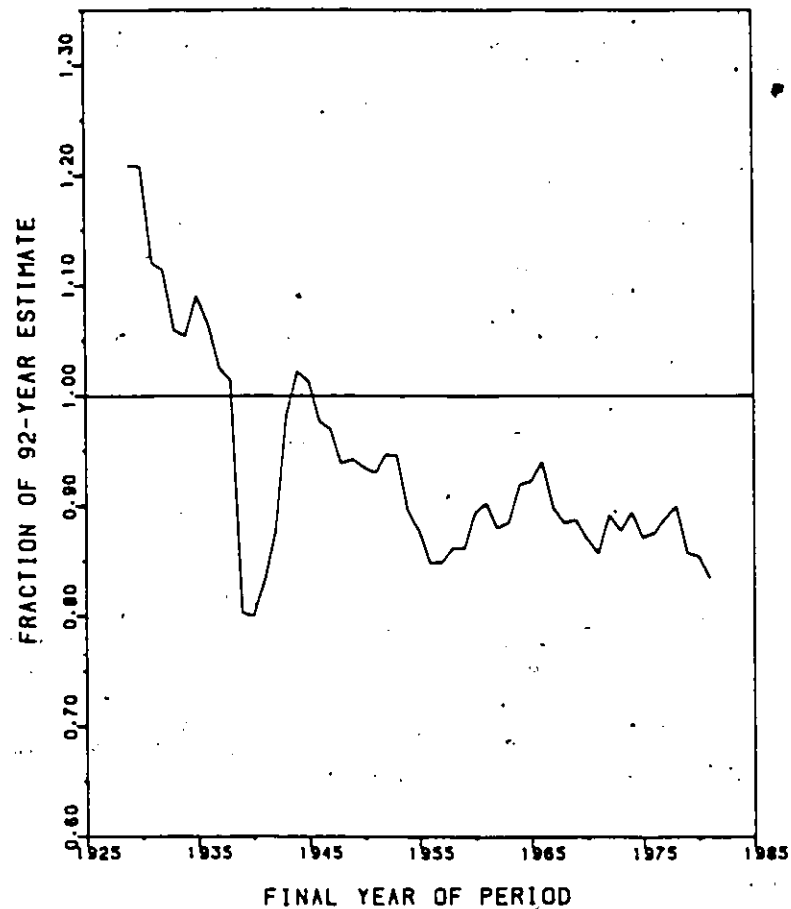


FIG. 16: 40-YEAR ESTIMATES OF MONTHLY COEFF. OF-SKEW.
OTTAWA CDA. RAIN. 1890-1981.

3.4 SOME BASIC MODEL CONSIDERATIONS

In this section, the first model parameters are defined and examined. Further parameters will be introduced in the next Chapter.

3.4.1 Economic Life

In order to properly estimate the probabilities of attaining a given level of reliability of demand using synthetic hydrology, an expected life of the rainwater collector must be estimated.

Criteria for the choice of this parameter are:

1. physical life of the tanks
2. maintenance to be given to gutters, roofs and expectation of repairs to minor flaws (i.e leaks) in the tank, etc.
3. changes in future demand expected
4. possibility of future changes in rainfall patterns
5. the need for a conservative design estimate
6. length of rainfall data available to estimate parameters
7. statistical nature of storage calculated by synthetic hydrology.

In rural areas of Eastern Ontario, the practice has been to build a cistern that will last as long as the house. This is at least 70 years and possibly 100. However, demand patterns cannot be expected to remain constant over a period

this long. In other areas of the world, costs may dictate a system with a shorter life - as low as 10 to 20 years - through use of less durable materials. As well, leaks and damage are expected and these would reduce the effective life of the tank.

Based on these physical considerations, a compromise estimate of economic life or parameter invariable period is 35-40 years, which is less than larger central reservoirs and dams. It is also a period that is still long enough to ensure that the data will give representative statistics.

3.4.1.1 Estimate of Parameter Error Due to Economic Life Choice

To obtain an estimate of the error in rainfall parameter estimation that such a length of data might produce for the Ottawa CDA data, assume the mean and variance are sampled from approximately normal, independent distributions. The error in the mean, E , is (p. 183 of [48]):

$$E < Z_{\alpha/2} \frac{\sigma}{\sqrt{n_e}} \quad (3.2)$$

which is stated with $1-\alpha$ probability and

where $Z_{\alpha/2}$ is a standard normal variate

σ is population standard deviation (assumed to be the 92-year estimate)

n_e is number of independent observations

Matalas and Langbein.[44] show that autocorrelated data contain less information because each value has some infor-

mation from its predecessor. Hence a given number of auto-correlated data have the same information content as a lower number of uncorrelated values. If n is the number of correlated and n_e is the number of uncorrelated data and ρ_1 is the lag-1 correlation of a Markov process, then

$$n_e = \frac{n}{\frac{1 + \rho_1}{1 - \rho_1} - \frac{2\rho_1(1 - \rho_1^n)}{n(1 - \rho_1)^2}} \quad (3.3)$$

The monthly rainfall data have $\rho_1 = 0.376$ and $n = 480$ (40 years) and therefore $n_e = 218$. At the 95% level, $z_{\alpha/2} = 1.96$, and $c = 40.3$. Thus E is less than 5.35. Since the mean monthly value is 55.4 mm., the percentage error is $5.35/55.4 * 100 = 9.7\%$

A similar analysis of variance (see p. 175 of [48]) with a two tailed chi-square at 95% confidence and a population variance of 1622 gives the percentage confidence limits for variance. The larger of the two limits is the combined percentage error. The percentage errors in the mean and variance are given in Table 3. This illustrates the point that the longer the life chosen, the better the estimate of population parameters. The 40-year economic life produces an error of under 10% in the mean and under 20% in the variance, errors which are a reasonable compromise between 20 and 50 year lives. These theoretical percentages agree with computed values in Figures 8 and 10. In more variable data in more arid climates, these percentages would be higher.

TABLE 3

Percent Error in Estimate of Mean and Variance for Various
Economic Lives. Ottawa CDA 1890-1981, Rain

Life (yrs)	Error in Mean (%)	Error in Variance (%)
20	13.7	25.3
35	10.3	19.3
40	9.7	18.1
50	8.7	16.3

3.4.2 Reliability Rating

Failure in a rainwater collector occurs when the demand is not met. The reliability level is a measure of the ability of the system to meet the demand. It can be calculated on the basis of either:

Time. The number of time periods that demand was fully met as a fraction of the total number of periods.

or

Volume. The total volume supplied as a fraction of the total demanded.

In general, time-based reliability is less than or equal to volume reliability or alternatively, storage based on time is higher than that based on volume.

3.4.3 Graphical Representation

To portray the results of the storage calculation in the most useful manner, demand and storage were represented on non-dimensional log-log plots similar to those in Jenkins et

al. [31]. Also, like Jenkins et al., it was assumed that the mean annual inflow was a reasonable upper bound for storage capacity and demand (i.e. demand and storage fractions are less than 1.). A lower bound of 0.01 was taken.

3.5 PRELIMINARY COMPARISON OF SIZING METHODS

3.5.1 Introduction

A preliminary assessment of various storage calculation methods was undertaken. Some of the work was reported in Schiller and Latham [66] where detailed data are provided for most methods. The data have been converted to demand and storage fractions for comparison.

The comparison was done for two stations using 15 years of monthly historical data for Ecum Secum, N.S. (station 8201700) for 1966-1980 and for Ottawa Lemieux Island, Ont. (station 6106052) for 1961-1975. Monthly fractions, coefficients of variation, and seasonal serial correlations for Ecum Secum and Ottawa (Lemieux) are plotted in Figures 17 and 18, respectively. Ottawa (Lemieux) data show a similar pattern to that of Ottawa CDA, but Ecum Secum shows less variation of monthly means over the year and over the data set.

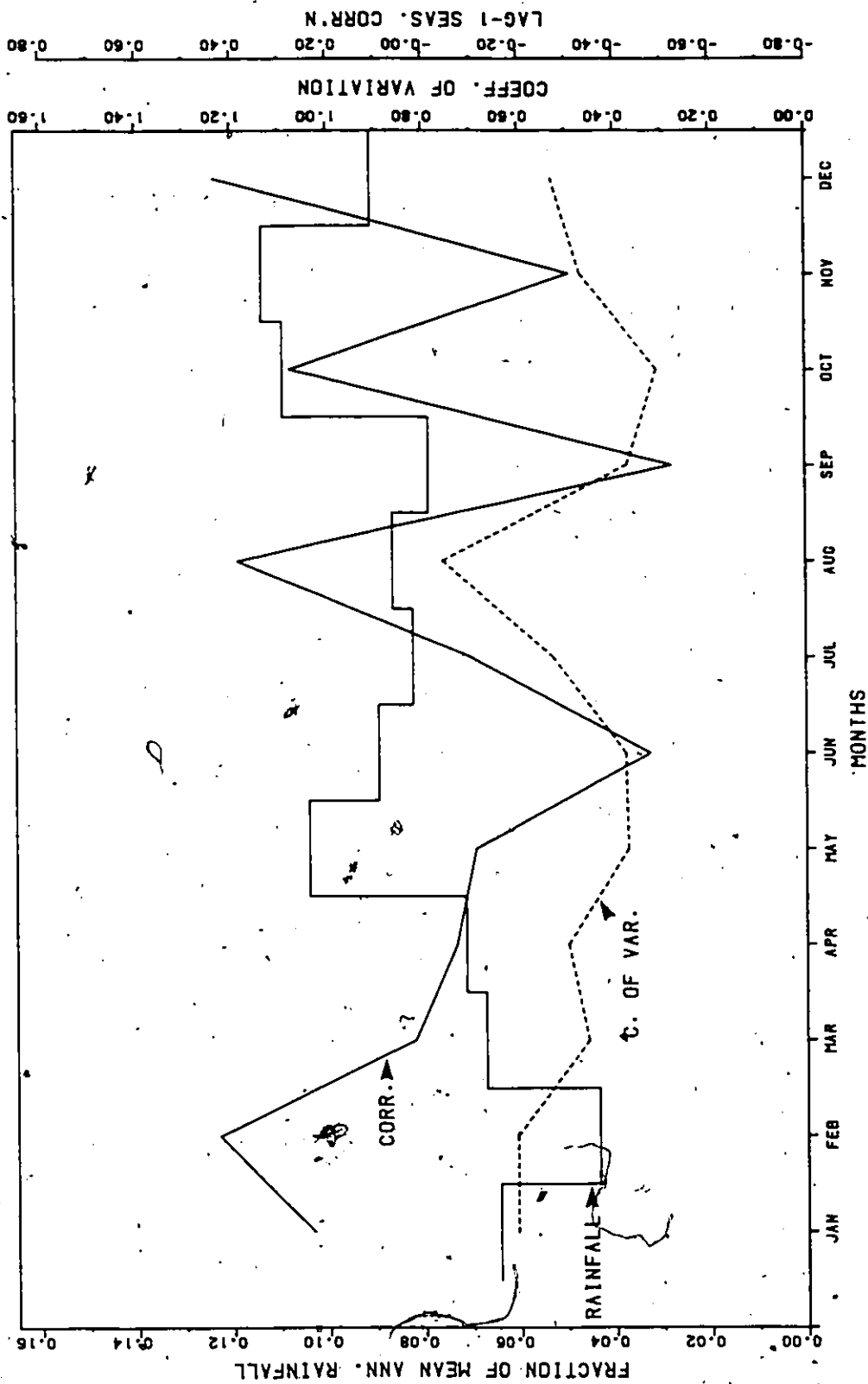


FIGURE 17. MONTHLY MEAN FRACTIONS, CV AND CORR., ECUM SECUM, N.S., 1966-1980

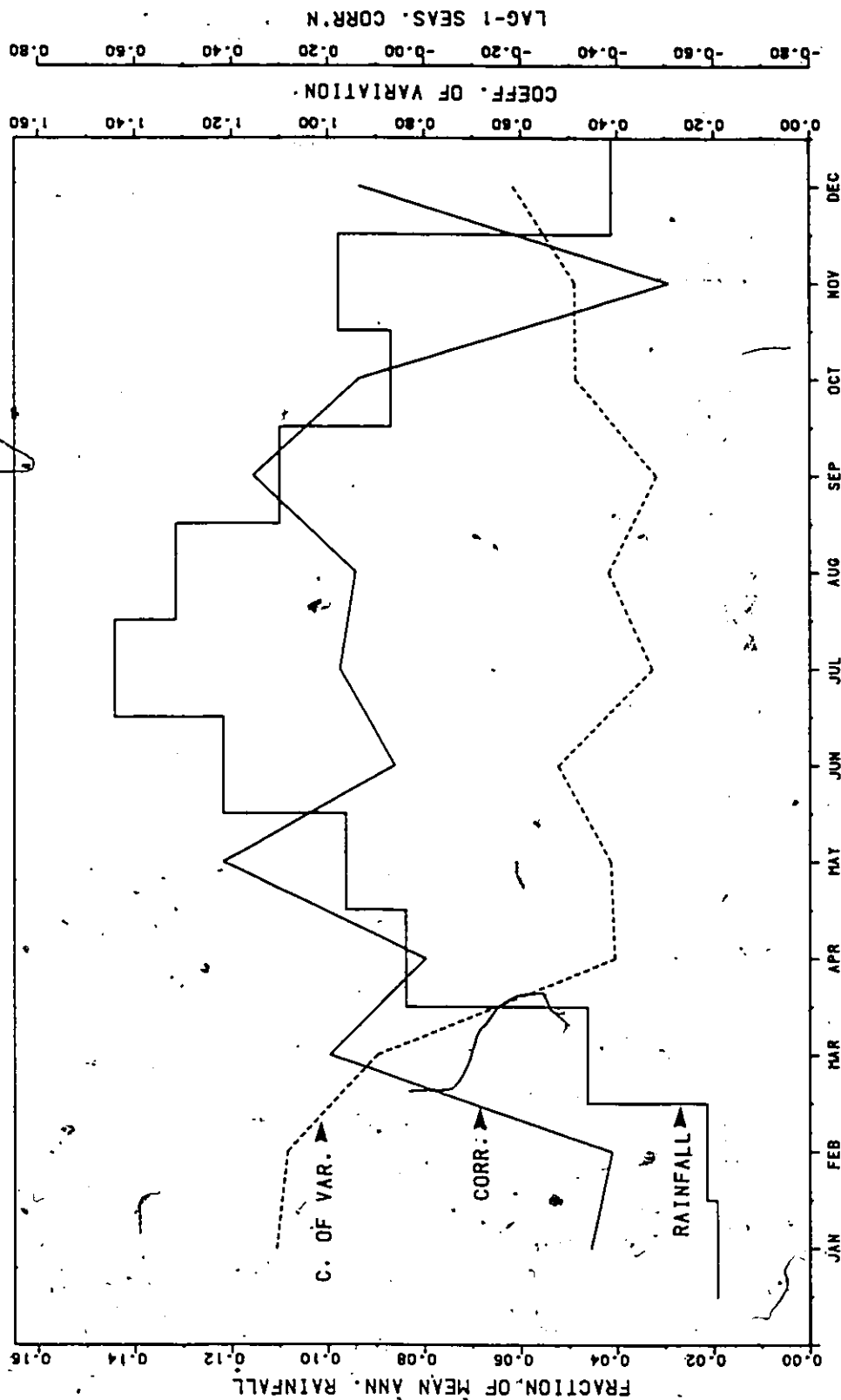


FIG. 18: MONTHLY MEAN FRACTIONS, CV AND CORR.. OTTAWA (LEMIEUX). 1961-1975

3.5.2 Methods

The methods compared were:

1. Mass Curve [61], [19]. It is designed for 100% reliability only. Adaptation of the familiar graphical presentation to the computer is:

- a) choose a starting month, k , (usually each month taken in turn)
- b) let $S'_{k,k} = 0.$, where the first subscript is a sequential counter
- c) find

$$S'_{j,k} = S'_{j-1,k} + d_j - r_j \quad (3.4)$$

for all data for $j > k$, or until $S'_{j,k}$ is negative where

$S'_{j,k}$ = is the storage at the end of month j for the calculation beginning in month k (depth)

d_j = demand in month j (in depth units)

r_j = rainfall depth in month j

- d) find S_{MAX_k} = maximum of $S'_{j,k}$

e) repeat first four steps for all k ,

f) Storage = maximum of all S_{MAX_k}

2. Probabilistic or Flow Frequency Method [59]. A series is manufactured from the data so that each period's flow in the series has the same recurrence

interval. A mass curve calculation is performed.

The computer algorithm is:

- a) pick a probability of occurrence (chosen here to be the same as the reliability)
- b) choose a flow period (in months: 2, 4,, length of data)
- c) calculate all rainfalls of this period length from data
- d) fit them to a Gumbel distribution and choose the value with the desired probability
- e) repeat steps b) to d) for all periods to get a resultant accumulated rainfall series
- f) perform a mass curve analysis on the series.

3. Perrens' method [52], [53]. A modified liberal behaviour analysis is done. Demand is reduced to 75% if the amount in store at the beginning of the month is less than full demand (rationing) and; outside sources of supply are available so that '5 m' are introduced at startup and lots of the same size are added if the amount in store at the start of the month is less than demand (stocking). Reliability is based on the number of times water is imported after startup (set at once in 5 years or 98.3% reliability by time).

The calculation algorithm is:

- a) set roof area, daily demand, storage volume

- b) perform the above behaviour analysis to find the number of times stocking is required
- c) plot the number of failures vs. storage for demand levels and roof areas.
- d) set failure rate at once in 5 years and read off storages for the number of failures = (years of data)/5. This is 3 in this case.

4. Jenkins' short method (p. 38, 55 of [31]) adapted here to:

- a) do mass curve analysis on 2 years of mean monthly values
- b) add storage = 1 month's demand
- c) multiply by 1.5

5. Conservative Behaviour Analysis with volume reliability and initial storage equal to the first rainy month's inflow.

All methods (except the Mass Curve and Jenkins' Short Method) were run with reliability levels (as defined for each method) of 98.3% to match that of Perrrens'. The results are plotted in Figures 19 and 20.

3.5.3 Results

While direct comparisons are not strictly accurate due to the different reliability evaluation methods used, the following conclusions can be drawn:

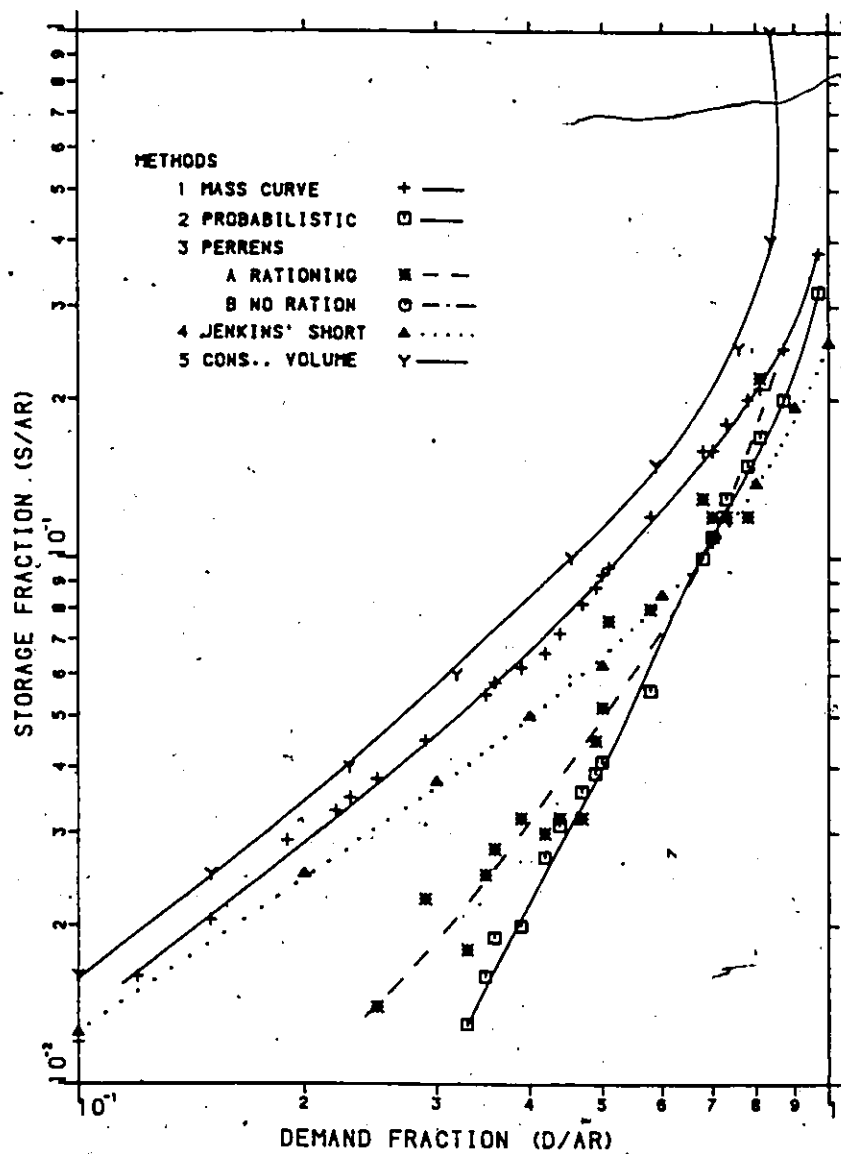


FIG. 19: DEMAND/STORAGE CURVES.
PRELIMINARY COMPARISON OF CALCULATION METHODS.
DATA: ECUM SECUM, N.S. 1966-80.

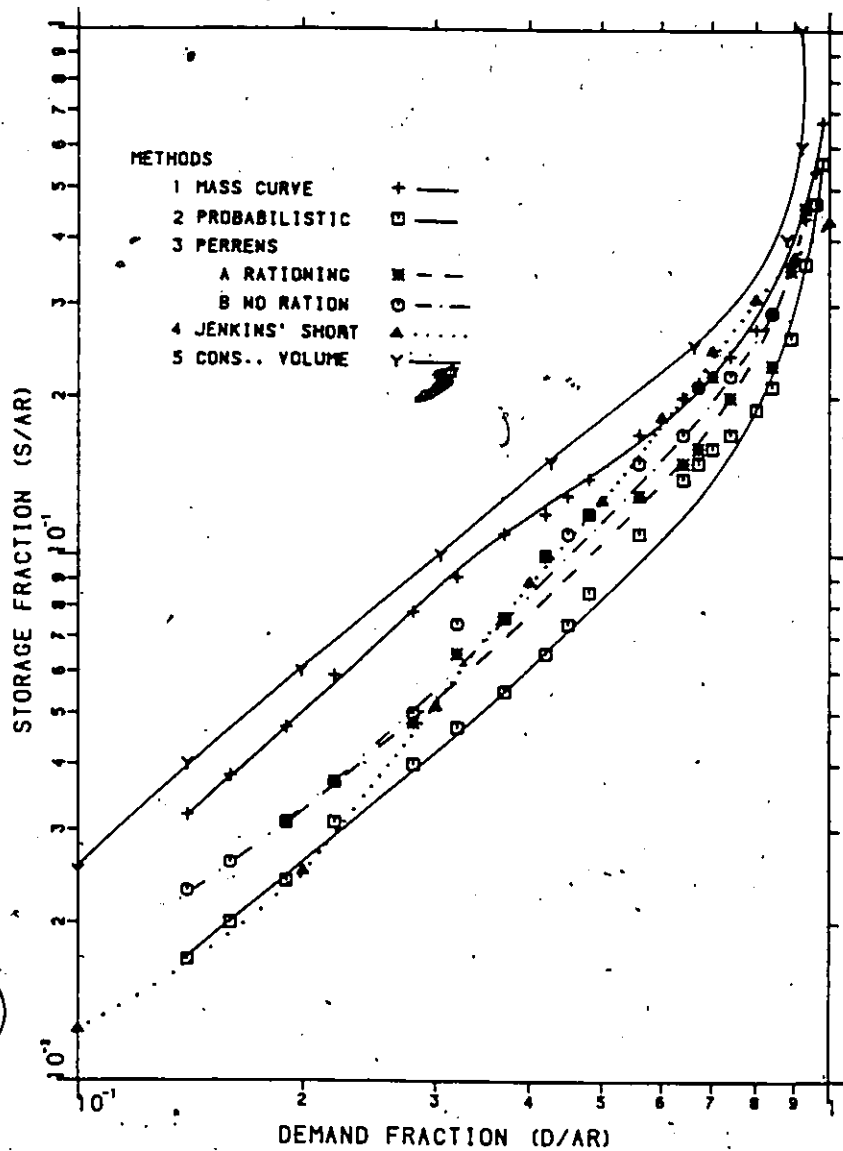


FIG. 20: DEMAND/STORAGE CURVES.
PRELIMINARY COMPARISON OF CALCULATION METHODS.
OTTAWA (LEMIEUX), ONT. 1961-75.

1. The largest values of storage are given by the model with a conservative behaviour analysis, followed by the mass curve, Perren's method with or without rationing and the Probabilistic method. This points up the conservative nature of the behaviour analysis and its suitability for design model calculations. Jenkins' Short Method can be compared to the other methods only by reference to the demand level and the particular rainfall pattern and is not consistently related to the other methods.
2. The Probabilistic Method values are much lower than expected. Intuitively one feels that it is a way of combining all of the worst rainfall periods. However, the minimum value for each period is not used but a larger one. Even if the minimum values were used, it would only be equivalent to the Mass Curve method because the required storage is defined by a set low-flow critical period which will be reproduced in the manufactured accumulated series.
3. Perren's rationing and stocking options reduce the required storage as expected. The Rationing and No Rationing plots in Figure 20 might be compared with the Mass Curve. External stocking reduces the storage more at low demand while rationing reduces it more at higher demands.

4. In all but the Conservative Behaviour Analysis with demand greater than 0.8, the storage required for Ecum Secum is markedly below that of Ottawa (Lemieux). The ratio of storage for Ottawa (Lemieux) to Ecum Secum is from 1.75 to 4.5 over the methods tested.

Chapter IV

DEVELOPMENT OF A STORAGE MODEL WITH BEHAVIOUR ANALYSIS

In this chapter, a storage model, NUPEARS4, which computes rainwater storage requirements is developed.

4.1 RATIONALE

In developing this model of storage, several guidelines were set:

1. The model should be as simple as possible. The basic calculation should be easily understood by the model user. It should be readily alterable so that further research can be used to improve the model. The operation of the equations involved should not become lost in the calculations using them.
2. The algorithm should mimic the actual operation of a system and should be independent of the data or data statistics fed into it.
3. For design purposes, the model should be conservative (tend to overestimate the required storage) to account for unforeseen events.

4.2 ALGORITHM

Jenkins et al. (p. 14 of [31]) discuss two extreme types for a behaviour analysis storage calculation. The first, the Yield After Spillage (YAS) or conservative model calculates the yield as the minimum of the starting storage value or the demand. It adds the rainfall to the previous storage, discards any above capacity and then subtracts the yield. The second, the Yield Before Spillage (YBS) or liberal model calculates the yield as the minimum of the starting storage plus the rainfall or the demand. It adds the previous storage and rainfall together, subtracts the yield and then spills any above capacity. A schematic of the difference is in Figure 21.

In equations:

Conservative :

$$Y'_i = \min(d'_i, S'_{i-1}) \quad (4.1a)$$

$$S'_i = \min(S'_{i-1} + r_i, S') - Y'_i \quad (4.1b)$$

Liberal :

$$Y'_i = \min(d'_i, S'_{i-1} + r_i) \quad (4.2a)$$

$$S'_i = \min(S'_{i-1} + r_i - Y'_i, S') \quad (4.2b)$$

where S'_i = Water in storage at end of ith period,

r_i = rainfall in ith period,

Y'_i = yield in ith period,

d'_i = demand in ith period

S' = capacity of reservoir

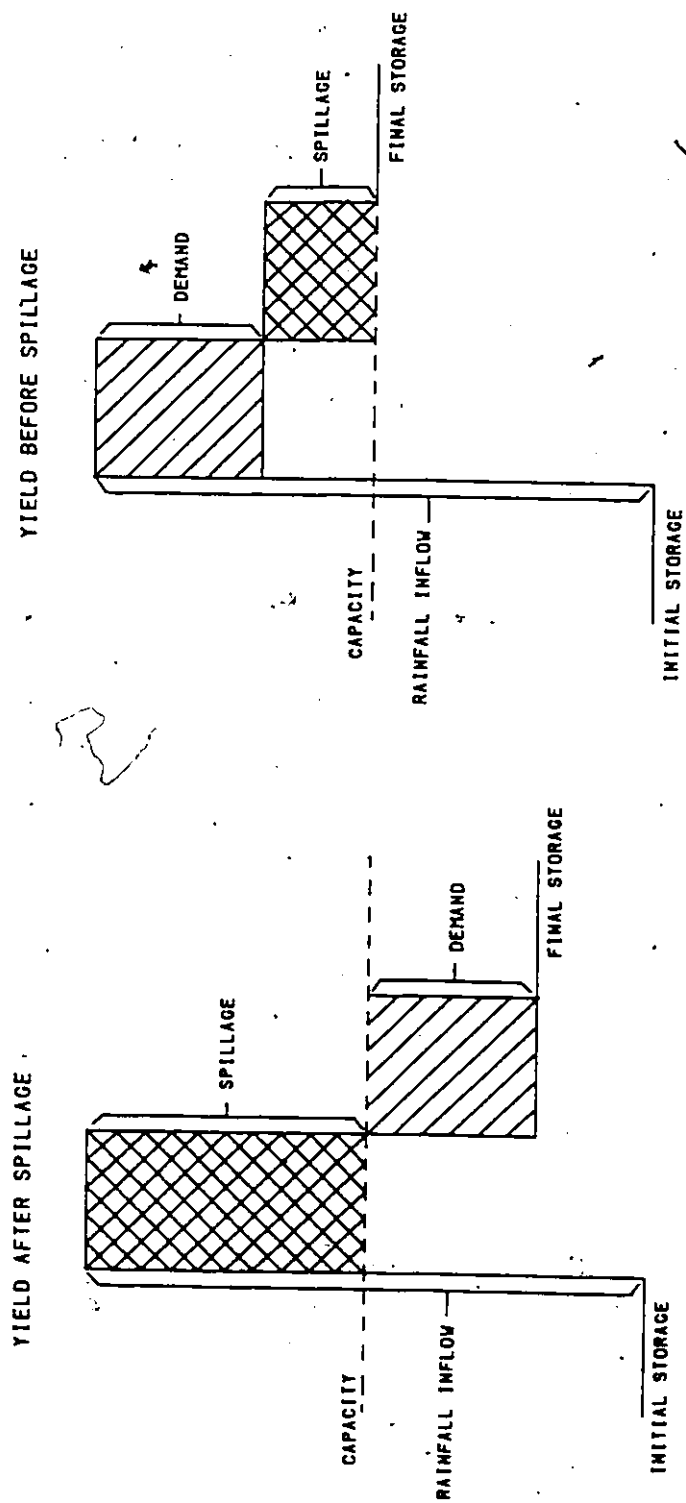


FIGURE 21: SAMPLE CALCULATION FOR YAS AND YBS BEHAVIOUR MODELS

S' and d' have been expressed as volume/collection area and have the units of depth. It should also be noted that the algorithm parameters can be divided by mean annual rainfall to produce a non-dimensional calculation.

In combination, the general algorithm is:

$$Y'_i = \min (d'_i, S'_{i-1} + \theta \cdot r_i) \quad (4.3a)$$

$$X = S'_{i-1} + r_i - \theta \cdot Y'_i \quad (4.3b)$$

$$S'_i = \min (X, S') - (1-\theta) \cdot Y'_i \quad (4.3c)$$

where $\theta = 0$ means conservative, and $\theta = 1$ means liberal. A family of models is thus available. Most algorithms used in the literature are of the liberal type except Jenkins et al. [31] and Pearson et al. [51] who used the conservative.

4.3 DEMAND PATTERNS

In most cases, a uniform rate of demand gives a reasonable first estimate of storage for design purposes. Accordingly, a uniform rate of demand was applied in the programme. Demand for each period (season) was given as:

$$(\text{yearly demand})/(\text{number of seasons per year}).$$

Cyclicity in demand can be taken into account by the adjustment of the storage value by the designer. If a non-uniform demand schedule is required on a general basis, the programme can be modified to account for it. The option to do this was not included in this model.

4.4 ADDITIONAL FEATURES

4.4.1 Stocking

If external sources of water are available, an empty reservoir can be stocked up to overcome a drought. Perrens [52] suggested a set amount, 5000 l., equal to a truckload which was added as a starting volume and in any case when the amount in store was less than the demand for the period.

Stocking was offered as an option. Since the programme's calculation was done in terms of fractions of mean inflow, a set volume could not be used. However, a week's demand was used as the stocking volume. Perrens in a later paper (p. 310 of [55]) suggested a ten-day supply.

4.4.2 Rationing

Perrens [55] and Hoey and West [26] studied demand levels with rainwater collectors and found that users reduced demand during drought. Perrens quantified this by a linear reduction of demand over the period from 100% to 50% or an equivalent drought period demand of 75% of normal demand.

Perrens' rationing was incorporated in the programme as an option but was not used in the models in this thesis. For simplicity in writing the WARMUP subroutine it was not included there.

4.4.3 Reliability Levels

Up to eight reliability levels could be entered for calculation. If no choice was made, the reliabilities of 100%, 99%, 90%, 80% were calculated automatically.

The storage programme was written to incorporate both time and volume measures as options and the level of reliability could be set. At the level of $x\%$, it means that $x\%$ of demand is supplied or the full demand is met $x\%$ of the time.

A volume-based reliability is chosen for most calculations carried out in this thesis because:

1. it provides a "softer" reliability value, i.e. smoother, because failure to meet demand on a time basis causes a fixed drop in reliability of $1/\text{number of months}$ (0.002 for 40-year case)
2. it makes intuitive sense that the concern of users is about how much water they have to use, rather than whether or not the system will meet their whole demand. This reflects the elasticity of demand.
3. Klemes et al. (p. 748 of [40]) summarized others in saying:

It has been often pointed out that the economic impact of failures in water supply can usually be best related to the volume of water deficit.

4.4.4 Dimensionless Calculations

The non-dimensional quality of the demand/storage/reliability representation could be exploited in calculating the coordinates from input data by doing the calculations with data that was non-dimensionalized by dividing by the mean annual rainfall. This is valid because the monthly inflow is Axr (A = area, r = monthly rainfall) while the average annual is AxR (R = mean annual rainfall) so that the fraction for the month is Ar/AR or r/R . If demand and storage are thought of as a depth of rain on the collection area, they too can be non-dimensionalized as a fraction of mean annual rain. In short, because the area used is assumed constant, it does not enter the calculations at all. Therefore, demand fractions can be chosen and the calculations run to get corresponding storage fractions with reference only to the mean annual rainfall.

4.5 RUNOFF COEFFICIENT

No allowance was made for runoff losses in the calculations. It was assumed that losses could be accounted for by a runoff factor whose effect is the same as if it were applied to the mean annual rainfall, R . Because the scaling of the input values does not affect the dimensionless storage curves, the runoff coefficient would only relate to the conversion from non-dimensional numbers obtained from the graph to dimensionalized volumes.

4.6 DATA SERIES TIME INCREMENT

The model was constructed to handle daily, weekly or monthly data, as desired. Weekly data is generally not available and must be produced from daily figures. It was not used in this thesis. No provision was made for different lengths of months.

4.6.1 Daily Data vs Monthly

Daily data and calculations would be expected to give a more precise answer because changes within a month are considered. These changes would be missed by a monthly calculation. The number of daily calculations and the memory requirements are thirty times those of monthly data. While a high-memory, high-speed mainframe computer has little trouble with these requirements, microcomputers might have some difficulties.

Monthly data is more easily obtained for most areas of the world because they can be published. They are more quickly entered on a machine, as opposed to daily data which are usually handled on magnetic tape. There are fewer calculations involved and less memory required so small computers can be used. However, monthly data may be too coarse and the accuracy to which the storage value can be determined is low. Much greater attention must be paid to the form and parameters of the algorithm.

4.7 STARTING STORAGE

4.7.1 Introduction

Researchers (p. 9 of [15]), (p. 159 of [3]), (p. 745 of [40]) agree on the important effect that the starting storage has on the calculated reliability of a system for the behaviour analysis calculation being used in this thesis. A study of the effect and a comparison of several methods of calculation were carried out. The details of the study are presented in Appendix B. In this study, a new more accurate algorithm was found. It involved starting with a full reservoir and calculating the storage for one year of data at a time. The resultant storages were averaged to give the starting storage.

4.7.2 Inclusion in Model

A single average, full start initial value calculation was incorporated into the storage model as subroutine WARMUP. The programme has an option to choose this or a preliminary case in which the calculation does not begin until the first rainy month. The starting value is taken as the first (non-zero) entry. The justification for this procedure is that the conservative option is so severe that it cannot produce a 100% reliable system if the reservoir is initially empty (see the conservative yield equation).

4.7.3 Effect of WARMUP on Storage Calculation

NUPEARS4 was run with time- and volume-based reliability of 98.3% similar to the earlier tests and the results are plotted in Figures 22 and 23 with methods 1 and 5 of Section 3.5.2. From this it is seen that a model with a conservative behaviour analysis based on volume gives lower values than that based on time, but the conservative behaviour results are still greater than for the other methods considered. In the case of volume-based reliability, the effect of WARMUP is to reduce the storage required. This is most dramatic at demand levels above 0.9 where storage is reduced by 30% and more.

4.8 OUTLINE OF CALCULATION

The subroutine DBYR carried out most of the calculations. It worked in units of depth but produced values of storage and demand as fractions of mean annual inflow. Given a reliability level, for each storage level, it calculated the capacity and carried out a binary search over the logs of the demand fractions between 0.01 and 1.5.

It is noted from Jenkins' plots that storage covers the range from 0.01 to 1.0 while demand may not do so. Thus, in trying to find points on the Demand/Supply/Reliability curve, it was advantageous to choose the storage and calculate the demand corresponding to it. Thus, for each value of storage, a demand level was chosen and the data run

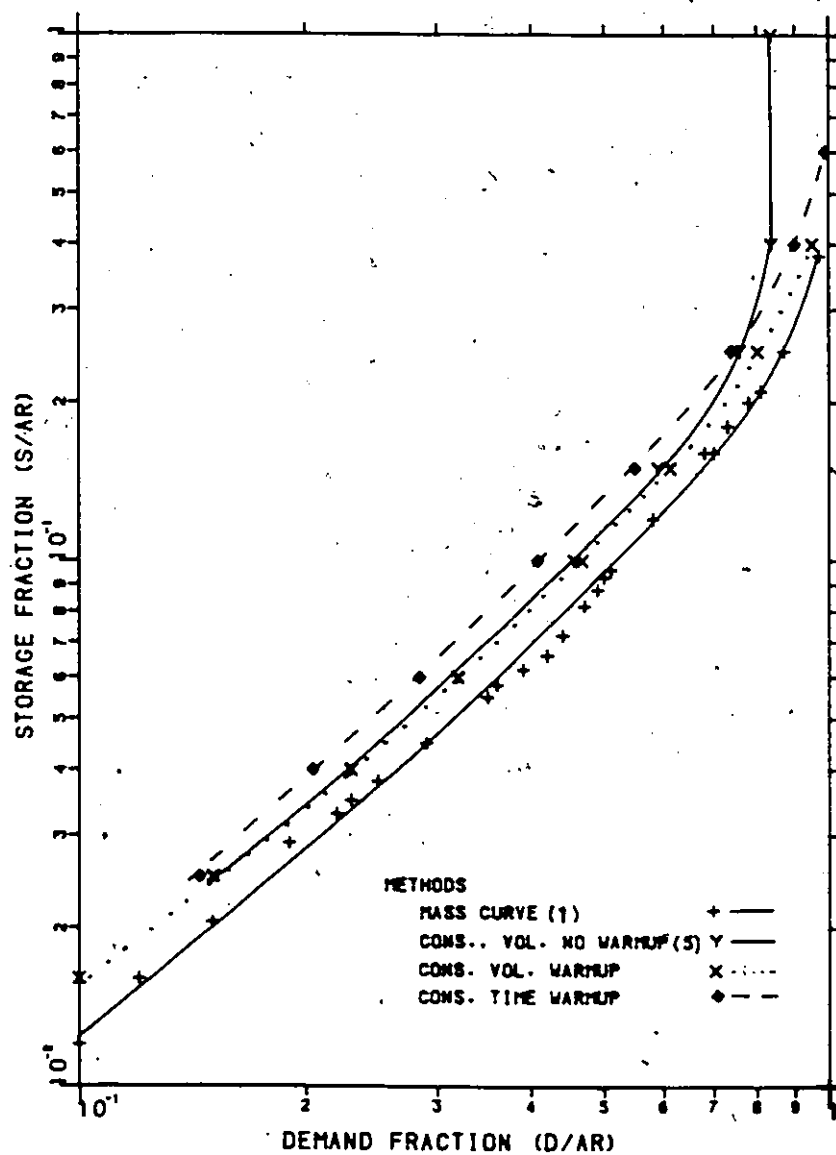


FIG. 22: DEMAND/STORAGE CURVES.
EFFECT OF SUBROUTINE "WARMUP".
DATA: ECUM SECUM. N.S. 1966-80.

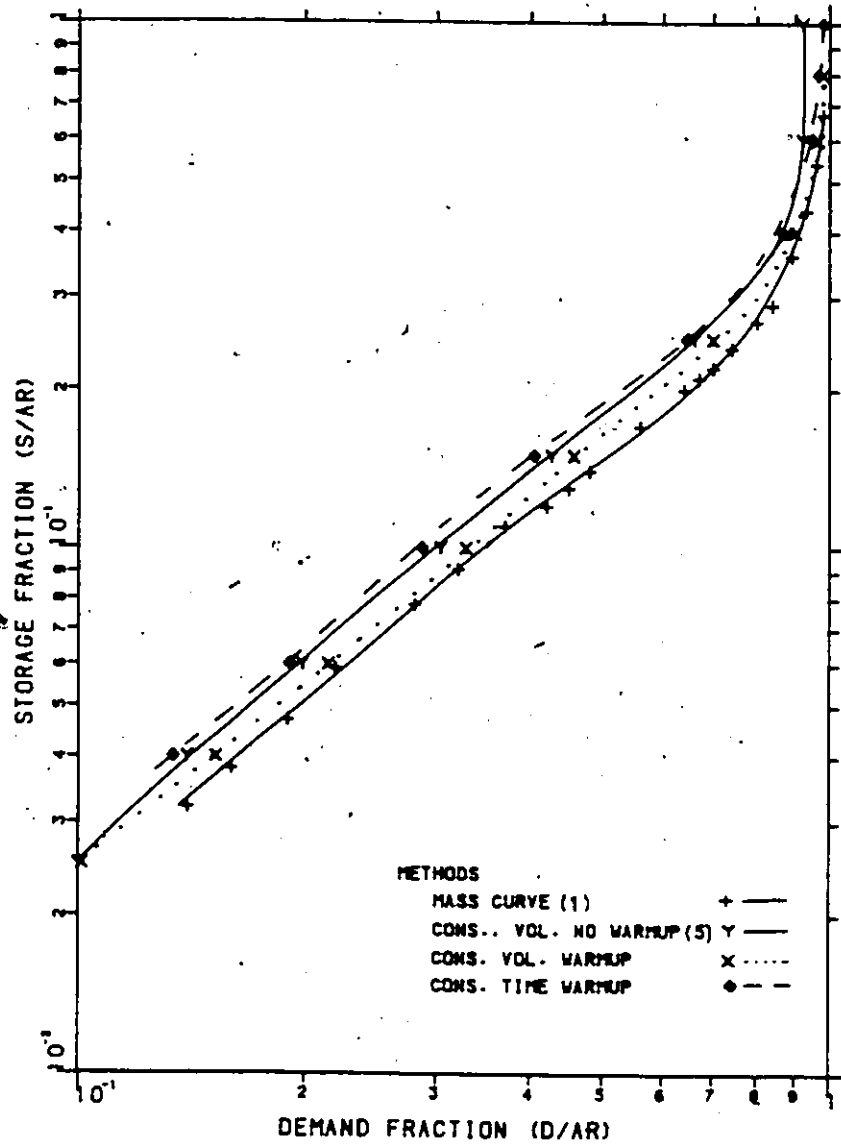


FIG. 23: DEMAND/STORAGE CURVES.
EFFECT OF SUBROUTINE "WARMUP".
OTTAWA (LEMIEUX), ONT. 1961-75.

through the chosen algorithm considering rationing and stocking as desired and calculating the reliability value as requested. Depending on this value, the demand fraction was altered and the complete calculation redone until either the calculated reliability was within some tolerance level of that desired or two successive demand fractions were within the same tolerance.

The complete programme was written in FORTRAN IV and ran under the G compiler on the University of Ottawa's Amdahl 470/V7A computer, which has an IBM VM/SP 370 operating system. A flow chart and a complete listing are given in Appendix E.

Chapter V

TESTING OF MODEL NUPEARS4

In this Chapter, daily and monthly models are compared and the monthly model is calibrated to approximate the daily model. Then, in order to examine the characteristics and features of the storage programme, NUPEARS4, various simple patterns of data were used as input to it. The results were examined with the use of the dimensionless plots of demand/storage/reliability.

5.1 DAILY VS. MONTHLY DATA

5.1.1 Calculation Options

Using the actual data for Ottawa CDA rain from 1942 to 1981, tests were made of the difference between the use of daily and monthly data by considering the following cases of θ (the algorithm parameter in equations 4.3 a, b, c) and the two methods of reliability calculation:

1. conservative calculation, volume reliability
2. conservative calculation, time reliability
3. liberal calculation, volume reliability
4. liberal calculation, time reliability

The storage values for reliabilities of 100%, 99%, 95%, 90% are plotted in Figure 24 for daily data and in Figures 25 to 28 for monthly data. The following can be noted:

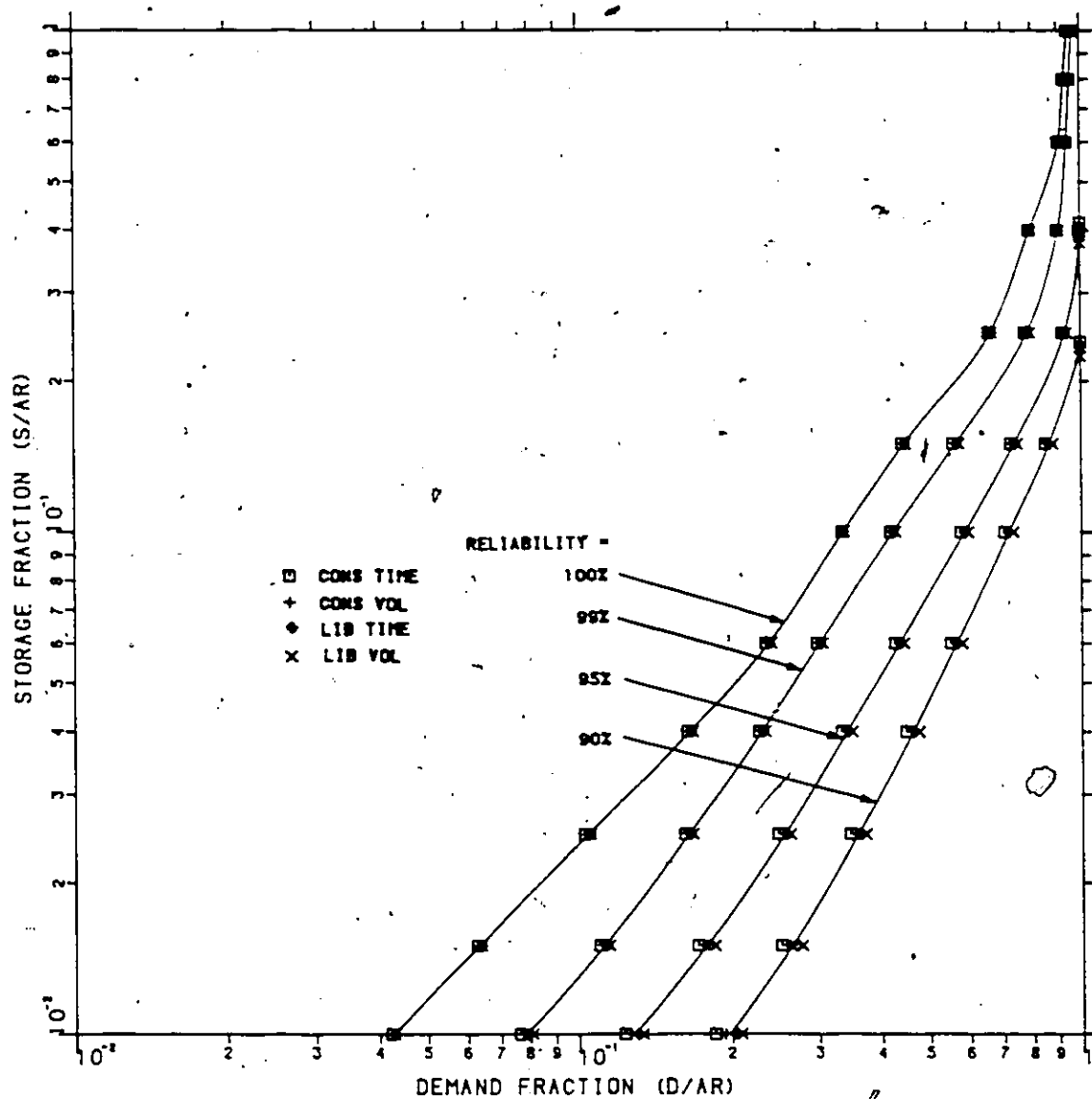


FIGURE 24: DEMAND/STORAGE CURVE - DAILY CALCULATIONS.
 RAIN, OTTAWA CDA, JAN 1942 - DEC 1981

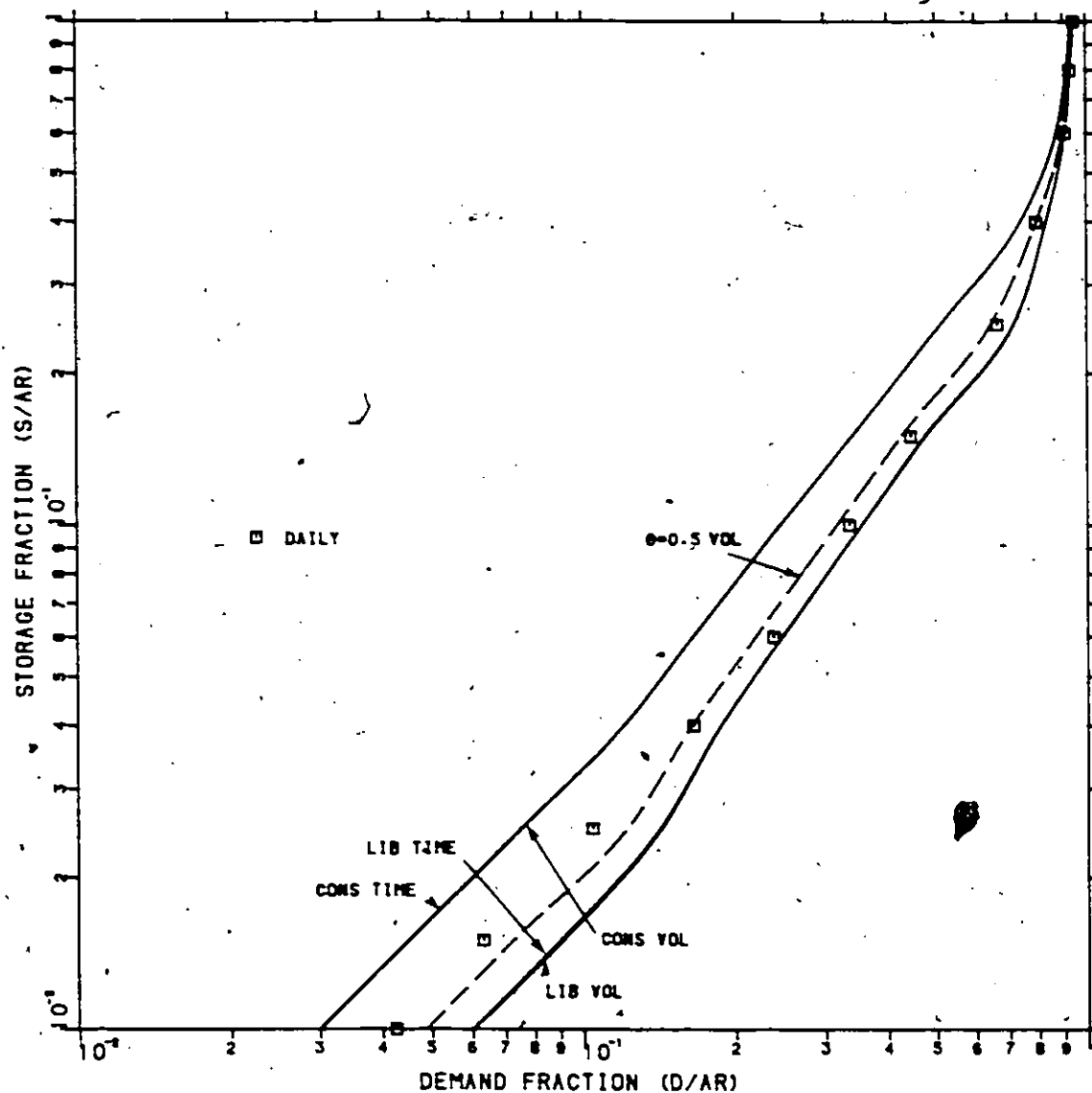


FIGURE 25: COMPARISON OF VARIOUS MONTHLY MODELS WITH DAILY MODEL.
 RAIN. OTTAWA CDA. JAN 1942 - DEC 1981
 100% RELIABILITY

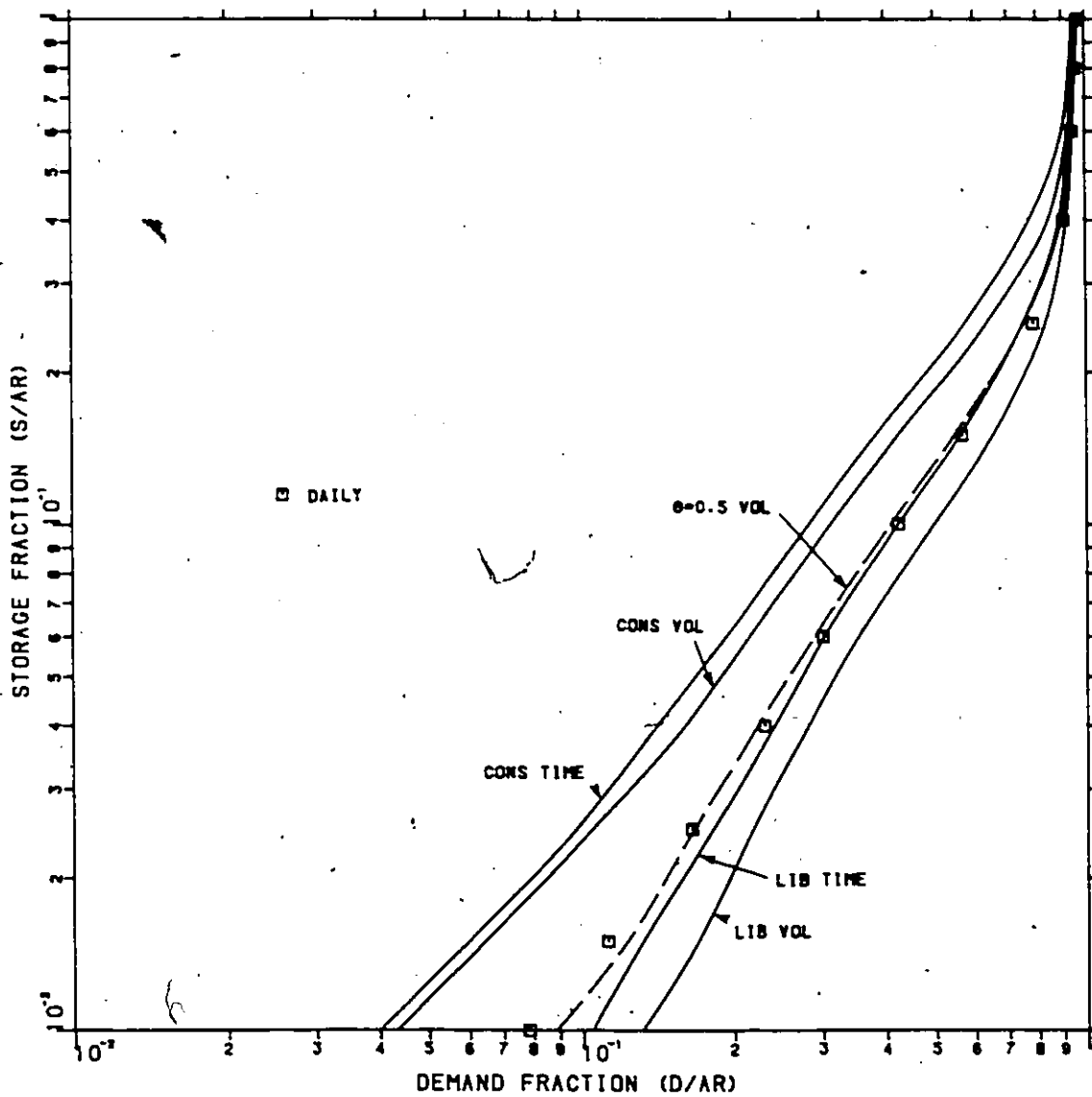


FIGURE 26: COMPARISON OF VARIOUS MONTHLY MODELS WITH DAILY.
RAIN, OTTAWA CDA, JAN 1942 - DEC 1981
99% RELIABILITY

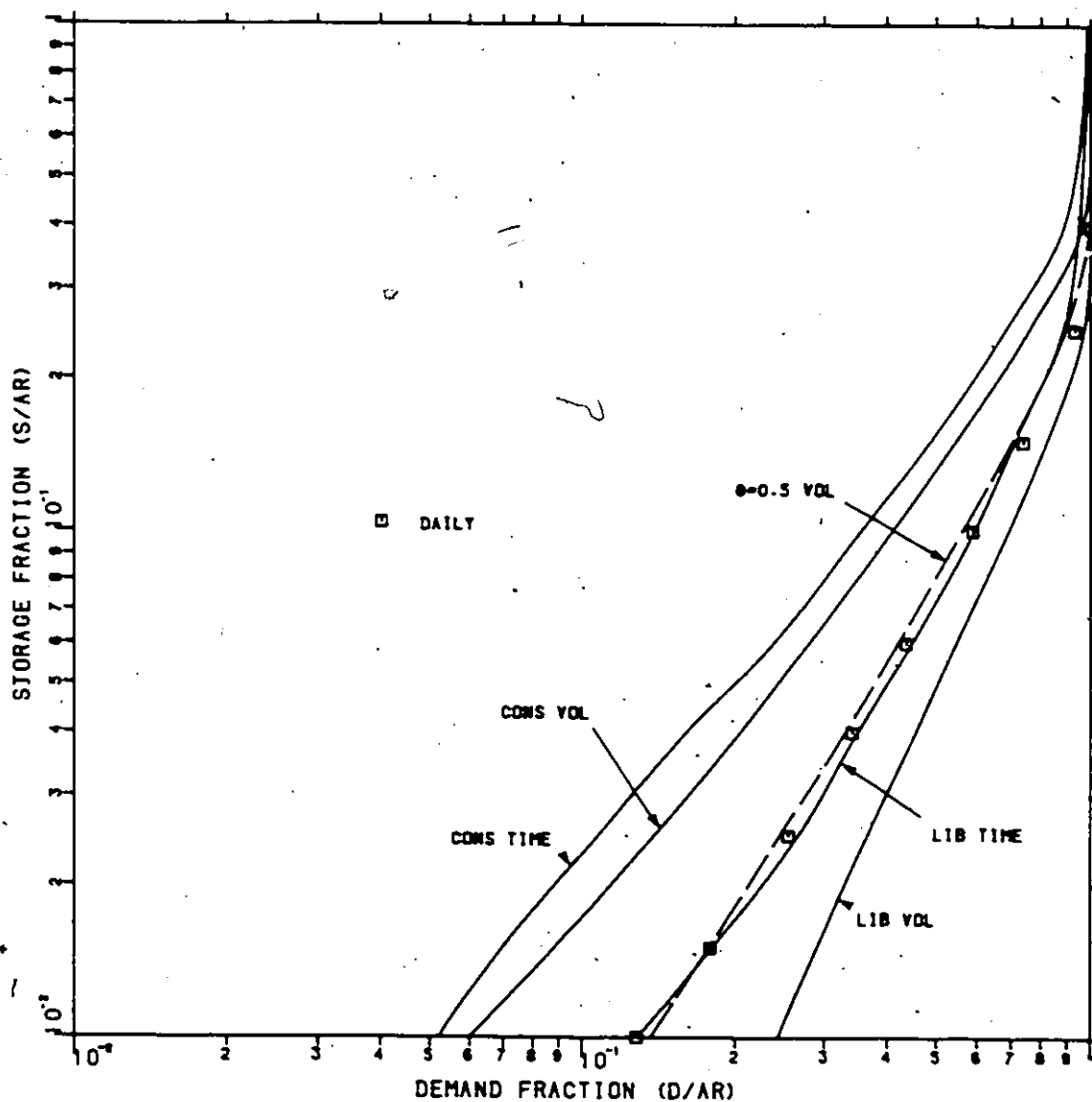


FIGURE 27. COMPARISON OF VARIOUS MONTHLY MODELS WITH DAILY MODEL.
 RAIN. OTTAWA CDA. JAN 1942 - DEC 1981
 95% RELIABILITY

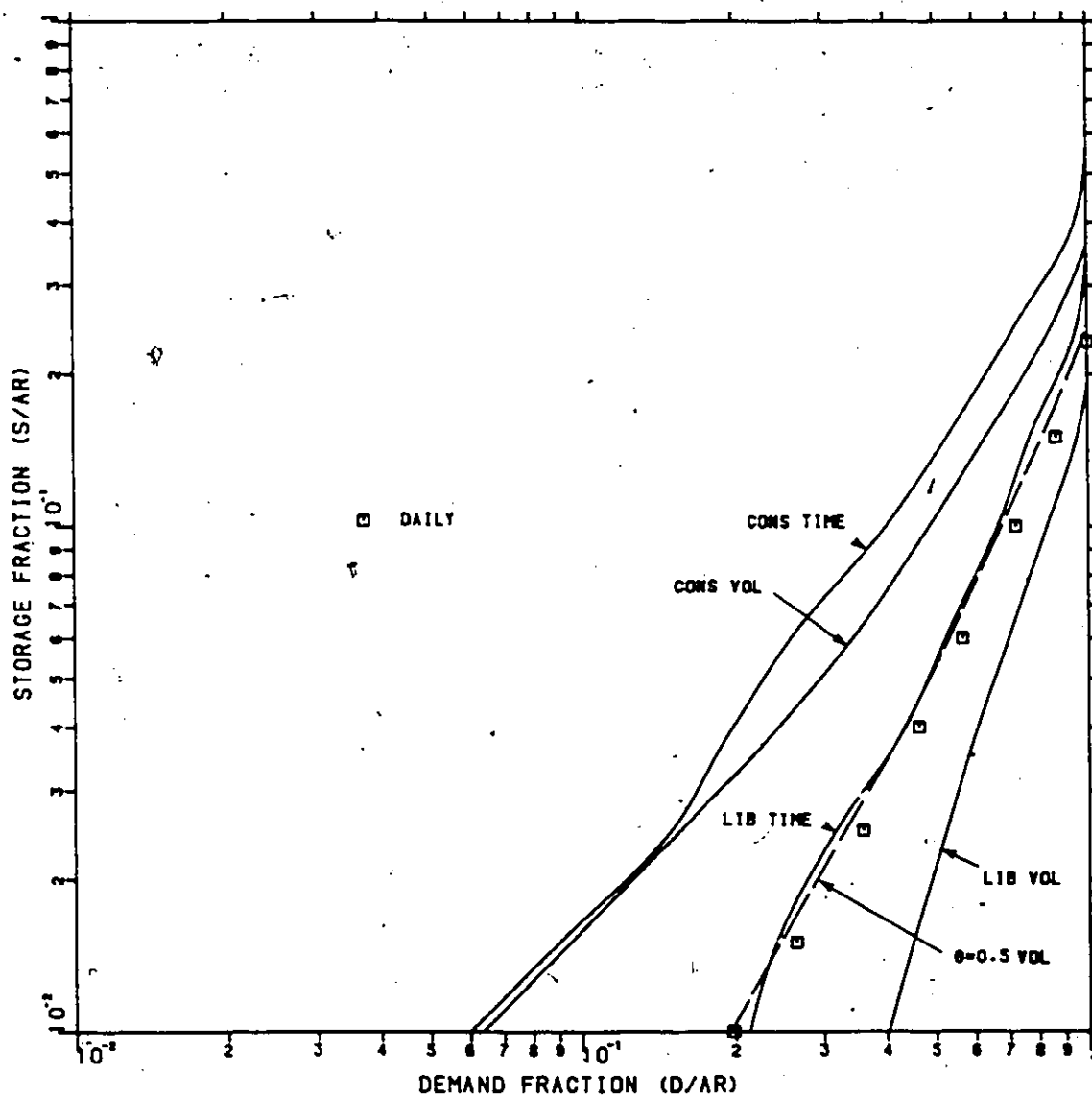


FIGURE 28: COMPARISON OF VARIOUS MONTHLY MODELS WITH DAILY MODEL.
RAIN, OTTAWA CDA. JAN 1942 - DEC 1981
90% RELIABILITY

1. The higher or further to the left a line is, the greater the storage required and the higher the reliability for a given demand level,
2. Except for high demand cases, the highest storage is obtained from conservative time calculations, followed by conservative volume, liberal time and liberal volume. Therefore, conservative calculations usually give greater storages than liberal and time reliabilities greater storages than volume.
3. Although it did not occur here, in some cases, especially for 100% reliability when WARMUP is not used, lines may not be within the scope of the graph. This is most likely the case with conservative calculations and points up the degree of conservativeness in these calculations. However, the 99% line is generally available.

5.1.2 Daily Data Results

Daily values are very close together for a given reliability, indicating that, as the time increment decreases, the closer to the actual storage values the four estimates get. Thus, there is good justification for taking the daily calculation as a standard of comparison. Moreover, the daily calculation should be used where the data is available. A representative line obtained by averaging all four individual lines was plotted along with the 4 sets of points in Figure 24.

5.1.3 Monthly Data Results

To compare daily and monthly values, the average daily points were plotted on the graphs of monthly calculations in Figures 25 to 28. In most cases, the daily lines fall between liberal and conservative monthly calculation lines although the daily calculation curve may fall below the Liberal, Time curve for lower reliabilities. This shows that the time-based reliability measure tends to lead to quite high storage values and that an intermediate monthly calculation is necessary. The conservative line overestimates storage by 30 to 150% depending on the value of demand, while the liberal calculations underestimate it.

5.1.4 Matching of Daily and Monthly Calculations

To be on the conservative side for design purposes, a method that produces a larger storage than the daily value would be advisable but the conservative monthly calculation may give storage sizes that are uneconomically large for the reliability desired. Two options are open to decrease the reliability of the conservative monthly calculations:

1. decrease the reliability
2. choose a different calculation algorithm by changing θ in equations 4.3 a, b, c.

The second case was examined by choosing $\theta = 0.5$ and using volume reliability calculations. The resultant lines are shown in Figures 25 to 28. Agreement with the daily points

is reasonable except for the lower demand levels of the 100% reliability case. However, for this work, a change in reliability from 100% to 99% when using the conservative monthly calculations was made. The advantages of this are:

1. The "fit" between the 100% daily line and the 99% monthly conservative volume reliability line is good in this case. See Figures 29 and 30.
2. The 99% monthly line will, in any case, overestimate the storage for 99% supply based on daily data and will at least guarantee this level of reliability, which is assumed acceptable to users.

5.1.5 Comparison of Some Daily and Monthly Models

Using the data for Ottawa CDA 1942-1981, four different means of calculation of demand/storage curves were compared with the 100% daily calculation. The methods used were:

1. 99% Conservative Volume behaviour method
2. 100% Liberal Time behaviour method
3. Mass Curve with demands adjusted for variable month lengths
4. Jenkins short method.

The results are plotted in Figure 31. Jenkins short method is clearly inadequate as it underestimates the storage required by up to 50%. The mass curve and the Liberal Time models are comparable and underestimate the daily storage by up to 30% although agreement is good at

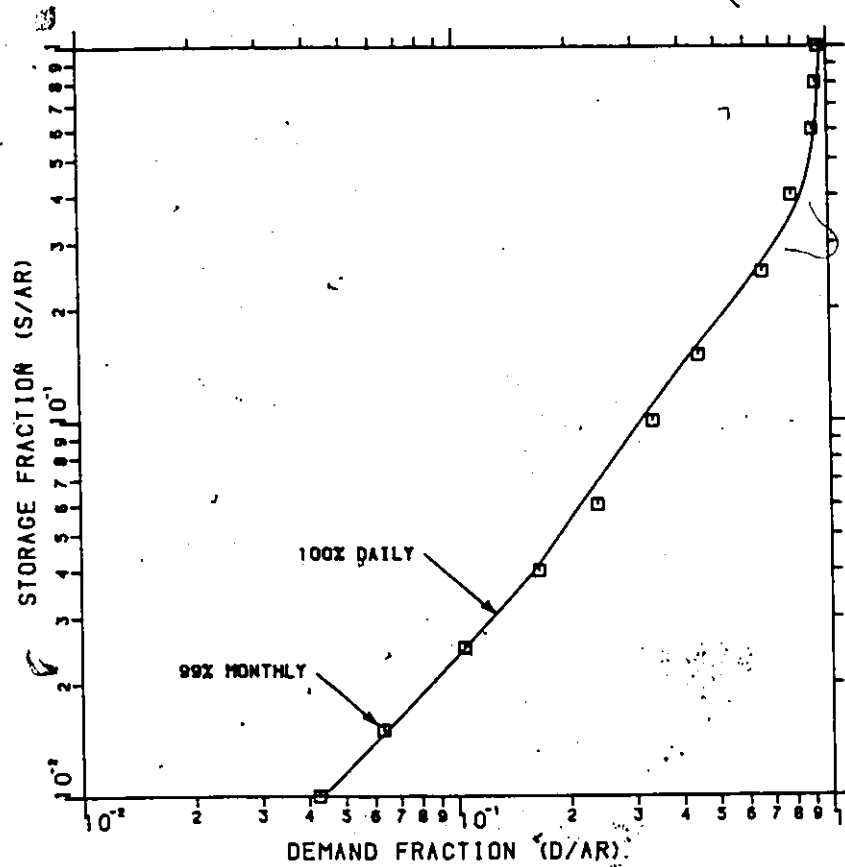


FIGURE 29: COMPARISON OF 99% MONTHLY
WITH 100% DAILY CALCULATIONS.
RAIN. OTTAWA CDA. JAN 1942 - DEC 1981

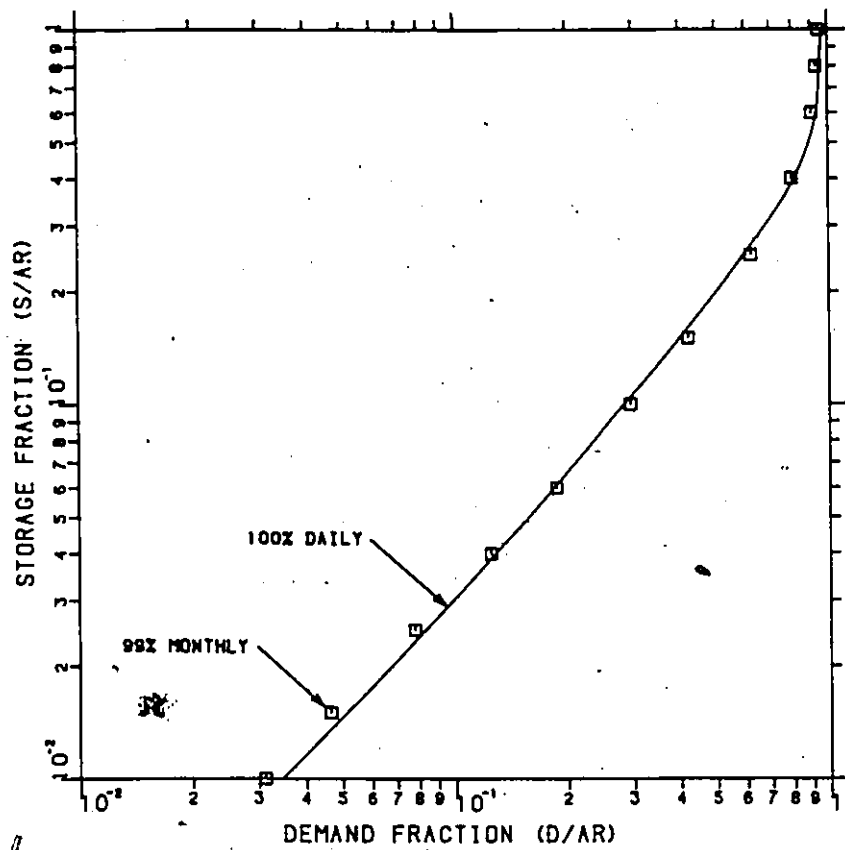


FIGURE 30: COMPARISON OF 99% MONTHLY
WITH 100% DAILY CALCULATIONS.
RAIN, OTTAWA CDA, JAN 1890 - DEC 1929

higher demands. The 99% conservative volume model overestimates the storage slightly at low demands and underestimates it at higher demands but is generally very close to the daily values.

5.2 SIMPLE DATA TESTING FOR BASIC RELATIONS

To show salient features of the storage algorithm and the storage pattern derived from it, several sets of specialized data were run through the model. The data were derived from monthly Ottawa CDA rain data for 40 years 1942-1981.

5.2.1 Effect of Scaling

The original data and a series with values twice the original data were run. The demand-storage values were identical showing that the demand/storage/reliability curve is independent of scaling the data. Thus, the data can be multiplied by any factor such as a runoff coefficient or a normalizing factor without altering the demand-storage relationship. This kind of linearity is similar to unit hydrograph assumptions and applications.

5.2.2 Constant Data

From now on, the conservative, volume-based, 99% reliability model will be used unless otherwise specified.

Next, test data with constant monthly values equal to the mean historical monthly value (57.2 mm) were run through the

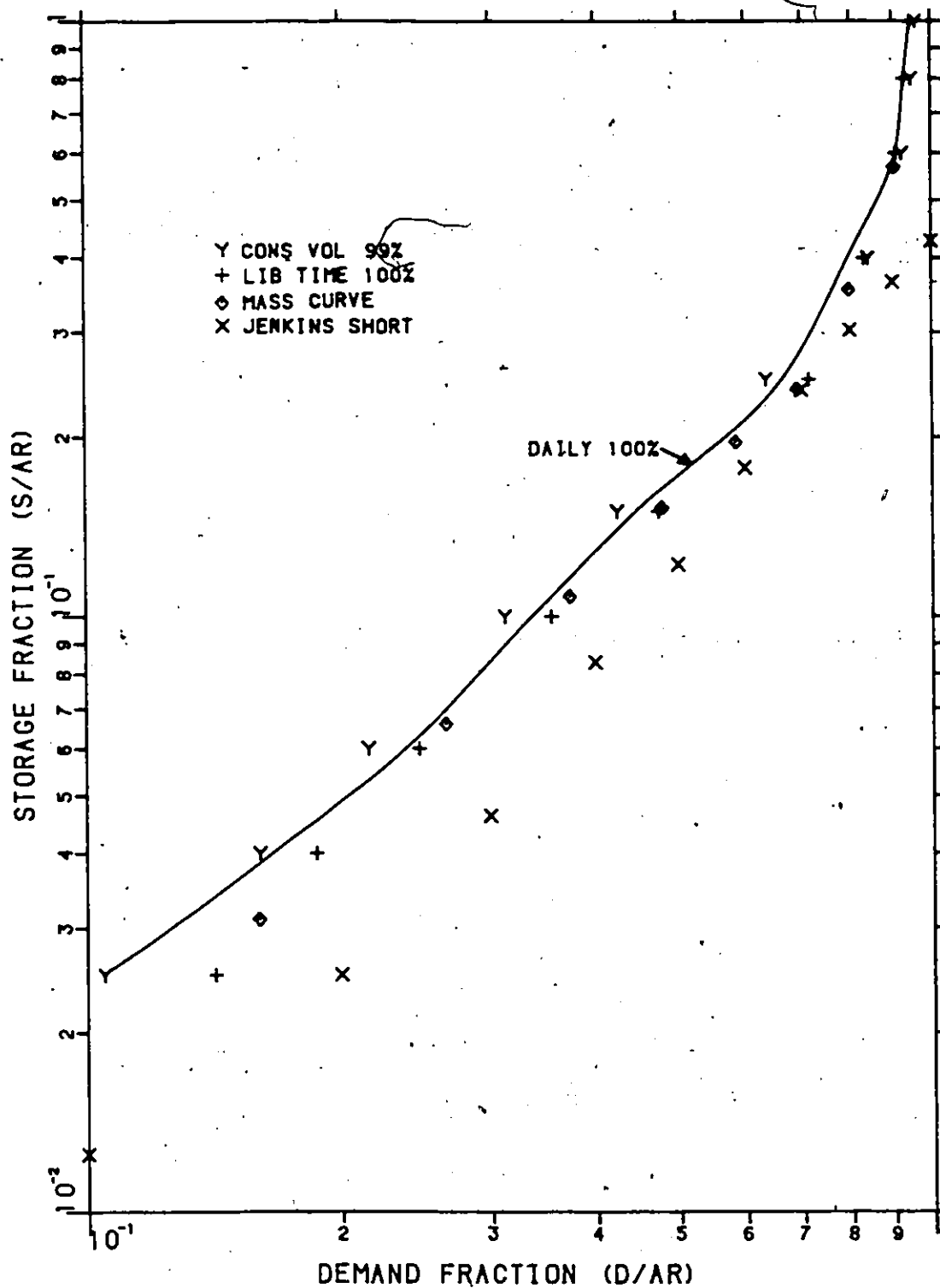


FIGURE 31: COMPARISON OF VARIOUS MONTHLY MODELS
 WITH DAILY
 RAIN, OTTAWA CDA, JAN 1942 - DEC 1981

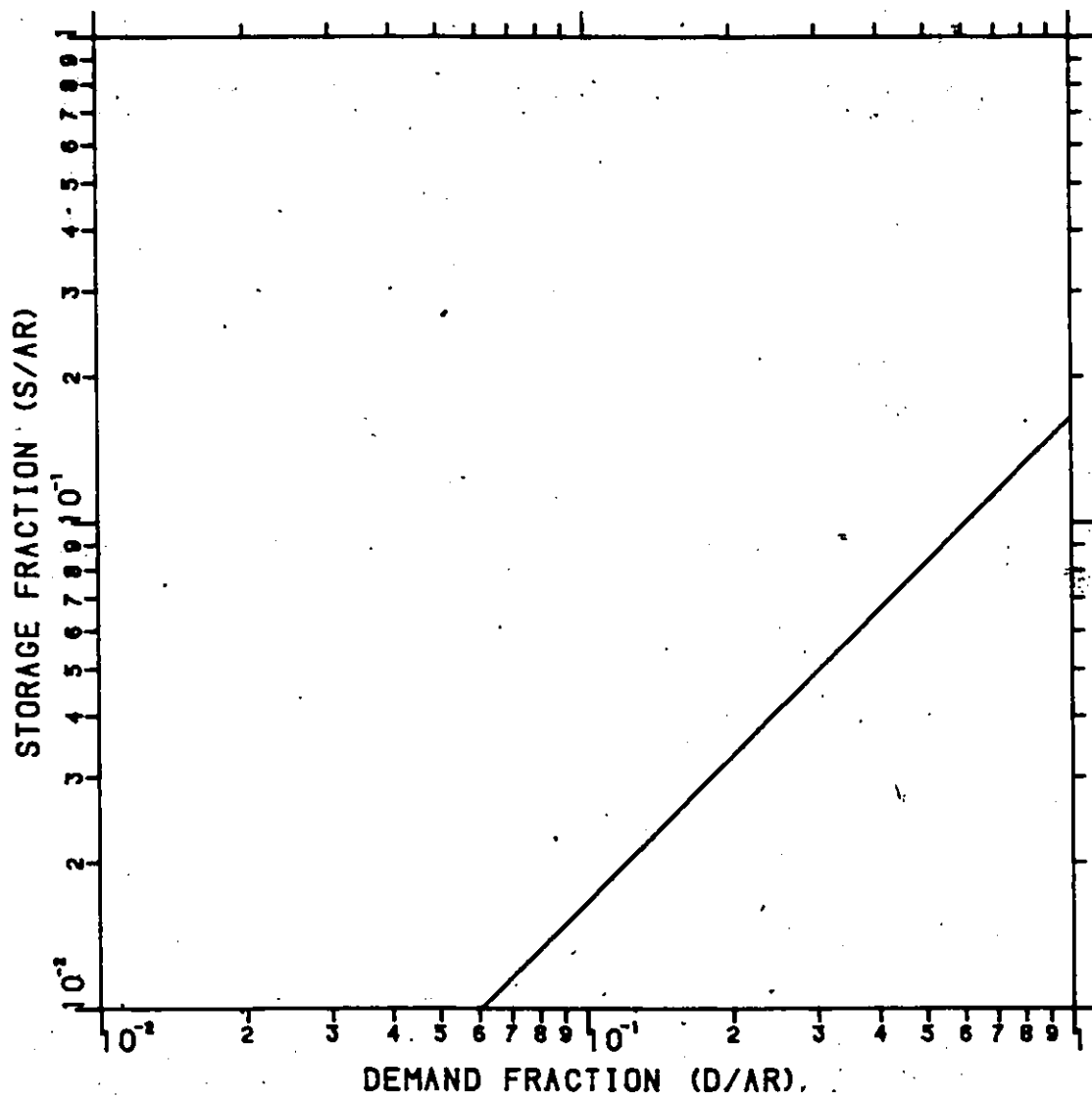


FIGURE 32: DEMAND/STORAGE CURVE .
ALL MONTHS CONSTANT.
99% RELIABILITY

programme. This was done to establish a baseline for comparison purposes. The result (Figure 32) was a definite straight line with the equation

$$S'' = 0.1650 D'' \quad (5.1)$$

This defines a lower bound for the storage values. The comparable line for 100% reliability is

$$S'' = 0.1666 D'' = D''/6 \quad (5.2)$$

showing the following general results of the model, which are independent of the actual rainfall values:

1. minimum storage is set at 2 months of demand
2. $S''(0.99) = S''(1.) \times 0.99$

5.2.3 Deficient Years

Continuing for the 99% reliability case, the effect of one deficient year was isolated and studied. In each case, one year (number 26 was chosen to give 25 years of calculations to be free of any starting volume effects) was set at 60%, 40%, 20%, 0% of the mean annual value. All months in the low year were constant. Those outside of this year were also constant as in the previous test data series but were adjusted to keep the overall mean constant. The results are plotted in Figure 33. From this, it can be seen that bending of the curve, i.e. increasing storage, occurs at about $D = \text{minimum annual inflow}$.

A similar analysis was done by changing only one month (June in year 26) in the series to 60%, 40%, 20%, 0% of the mean monthly value. The effect was minor.

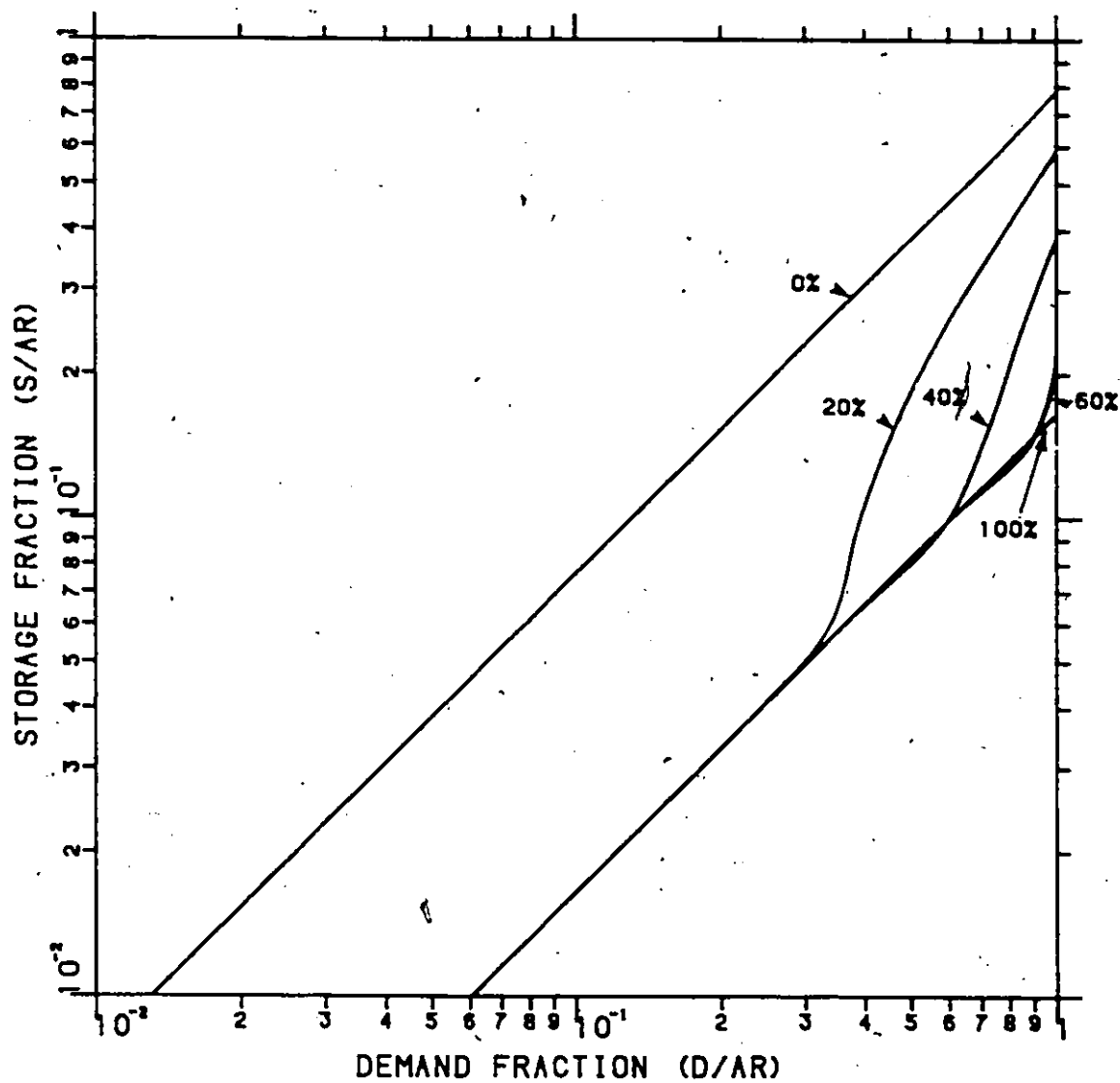


FIGURE 33: DEMAND/STORAGE CURVE.
EFFECT OF DEFICIENT YEAR -
YEAR #26 AT DIFF. LEVELS.
99% RELIABILITY

To show the effect of the annual rainfall totals, a plot for a series with monthly rainfall constant within each year but equal to $1/12$ of historical annual values is given in Figure 34. In the data, the minimum annual value was 0.627 of the average annual. It is observed that a bending of the curve after $D = 0.6$ appears to occur. This may indicate that the division between within-year and over-year storage is defined by a demand equal to the minimum annual inflow of the data series.

5.2.4 Cyclicity of Months

On Figure 35, plots are shown for:

1. actual data series
2. constant monthly data
3. monthly cyclic data that are the average values for each month (same average year repeated)
4. annually-scaled monthly cyclic values based on monthly means but with each year scaled by the annual values. The difference between this and the previous line gives the effect of the annual variation.

It can be seen that above $D/AR = 0.2$, increasingly larger amounts of the required storage above 2 month's demand are explained by the monthly cyclicity. The annual variation once again has a significant effect only at very high demands (greater than 0.8).

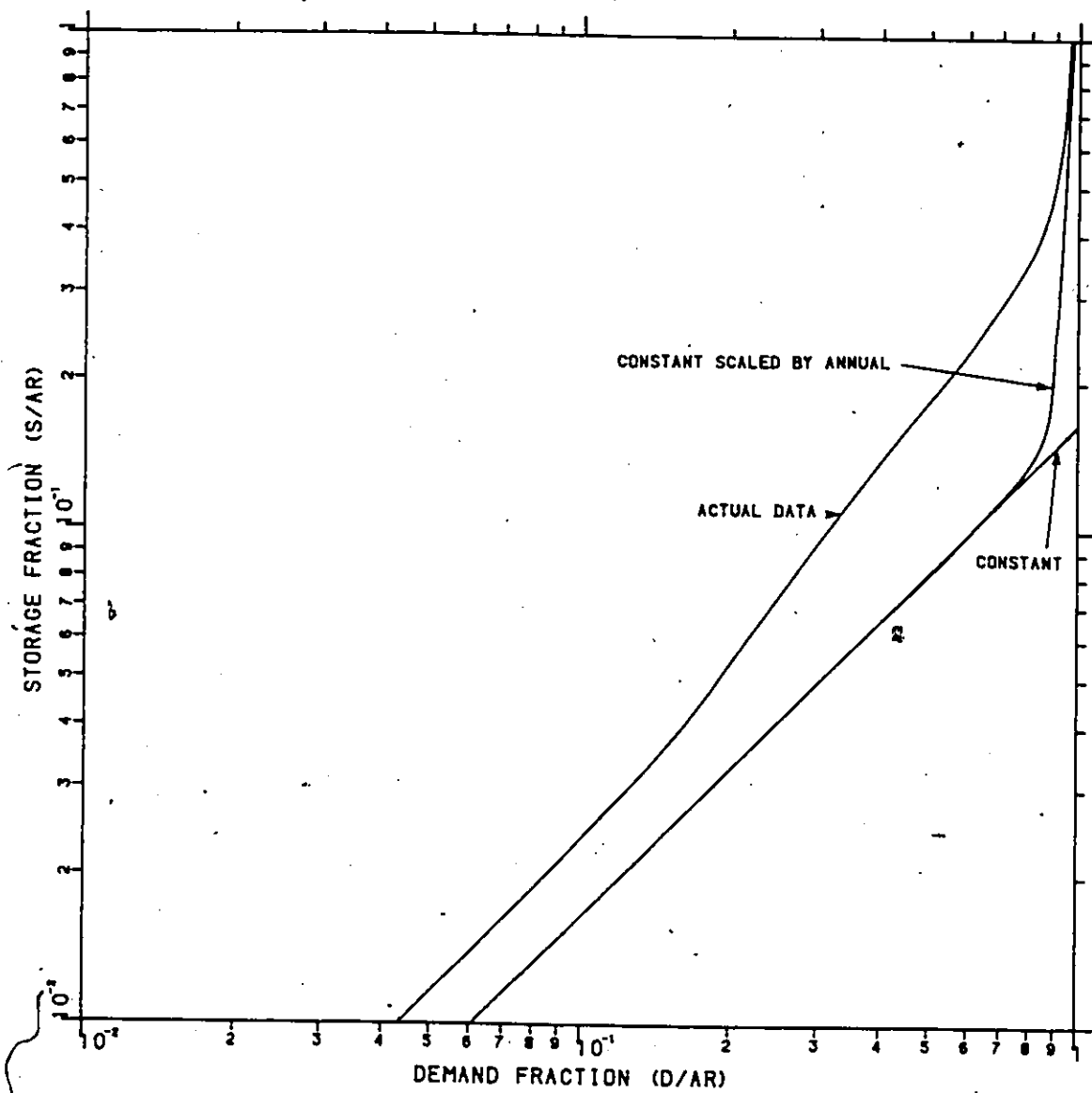


FIGURE 34: DEMAND/STORAGE CURVE.
 MONTHS CONST. WITHIN YEAR BUT SCALED BY HISTORICAL ANNUAL.
 99% RELIABILITY
 DERIVED FROM OTTAWA CDA RAIN 1942-81

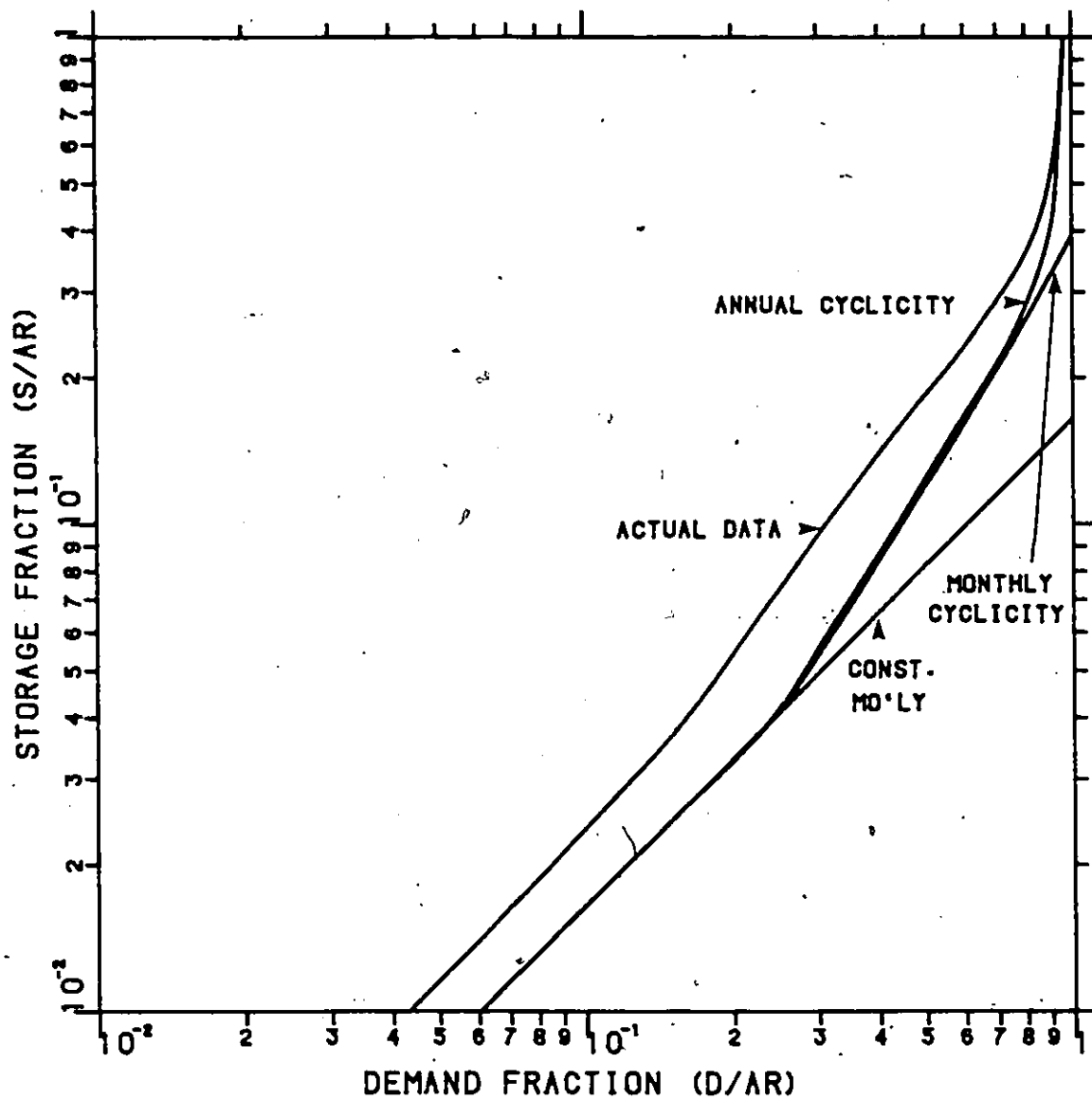


FIGURE 35: DEMAND/STORAGE CURVE.
EFFECT OF CYCLICITY.
99% RELIABILITY
OTTAWA CDA RAIN 1942-81

5.2.5 Length of Deficient Period

Tests were run with 1, 2, 3, . . . 12 consecutive months of year 26 set to 0.0 and the months of the other years held constant at the historical average. For the 100% reliability case, the effect was to cause the storage curve to rise the equivalent of one month for each month set to 0.0. For 99% reliability, (see Figure 36) there was very little increase in storage noted for 1 to 4 deficient months, but a significant increase (about 1 month's storage) occurs for 5 months. The reason for this is that $5/480 = 0.0104$ which is greater than $1 - 0.99 = 0.01$. This means that for up to 4 months, the 1% failure is absorbed by concentrating it in the drought months, but once the drought is more severe than the reliability shortfall, the system must add a month of storage to make it up.

5.3 SUMMARY

Of the effects examined, the one that appears to produce the greatest effect is the period of drought, or the number of months below a certain value. Next is the monthly cyclic nature of the data, which also defines a drought period. The fluctuation of the annual totals has an effect but only at higher demands and especially above a value = (min annual input)/(mean annual input).

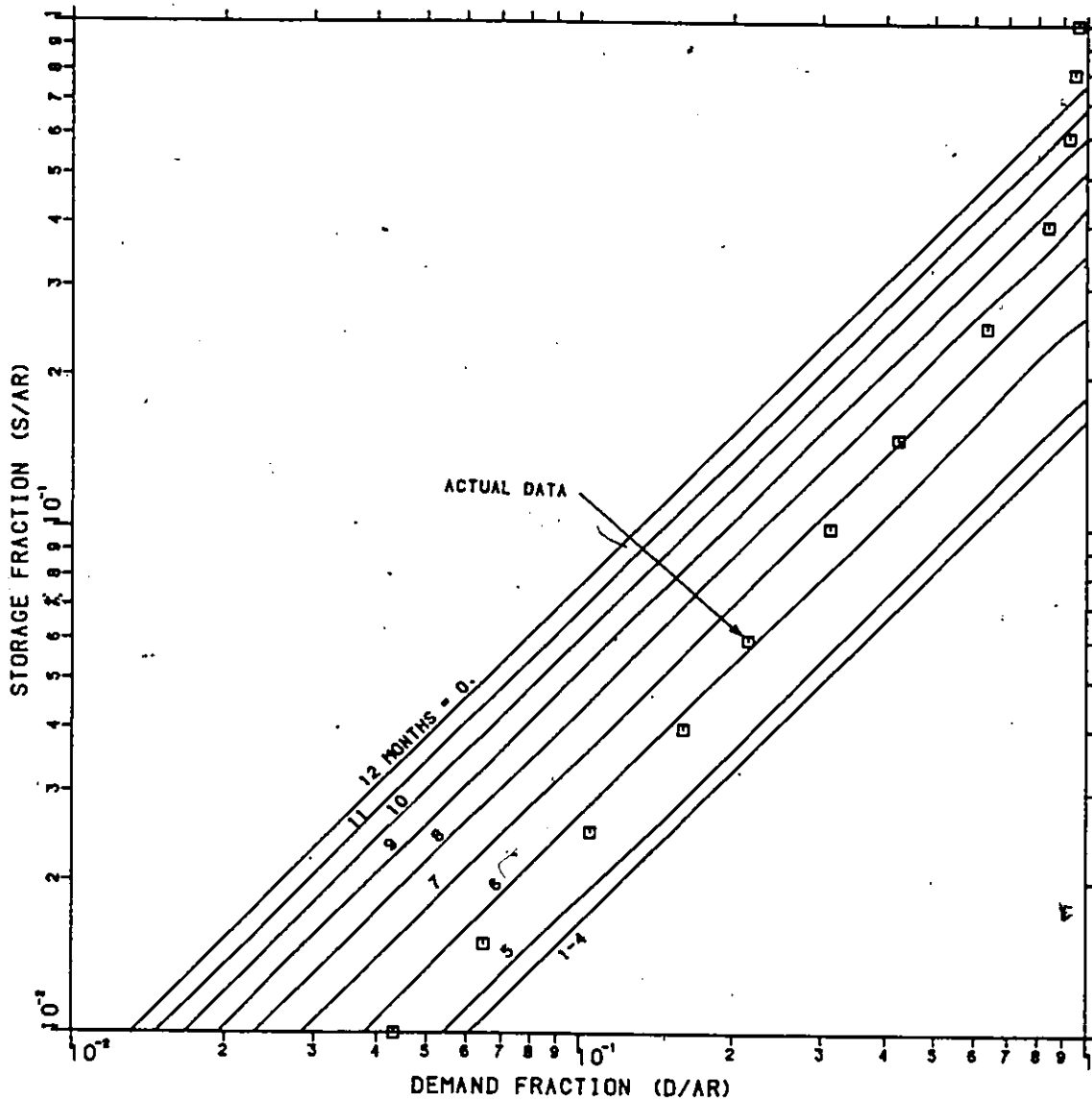


FIGURE 36: DEMAND/STORAGE CURVE.
EFFECT OF NUMBER OF DEFICIENT MONTHS.
99% RELIABILITY,
DERIVED FROM OTTAWA CDA RAIN 1942-81

Chapter VI

APPLICATION OF SYNTHETIC HYDROLOGY ANALYSIS

To apply the principles of synthetic hydrology to this problem, a new computer programme, CISTERN, was developed to generate data and calculate the required storage. A complete listing is given in Appendix E.

6.1 GENERATION OF RAINFALL DATA

In order to choose a model for generating standardized data, the Ottawa CDA monthly rainfall data were examined using the IMSL subroutine FTAUTO. The autocorrelation and partial autocorrelation structures were determined and plotted in Figures 6 and 37. A classic annual periodicity is evident in the correlogramme.

The data were then normalized by subtracting the monthly means and dividing by the monthly variances. The resulting data were again examined by FTAUTO and the results plotted in Figures 38 and 39. The significance level on the correlations in all cases was 95%. For normalized data, points of significance in autocorrelation were at lags of 10, 43 (and not shown on the graph: 53, 56, 99, 109, 115, 141, 209). In the PACF, significant points are at lags 10, 43, 53, 54, 95, 99. None of these is highly significant or of

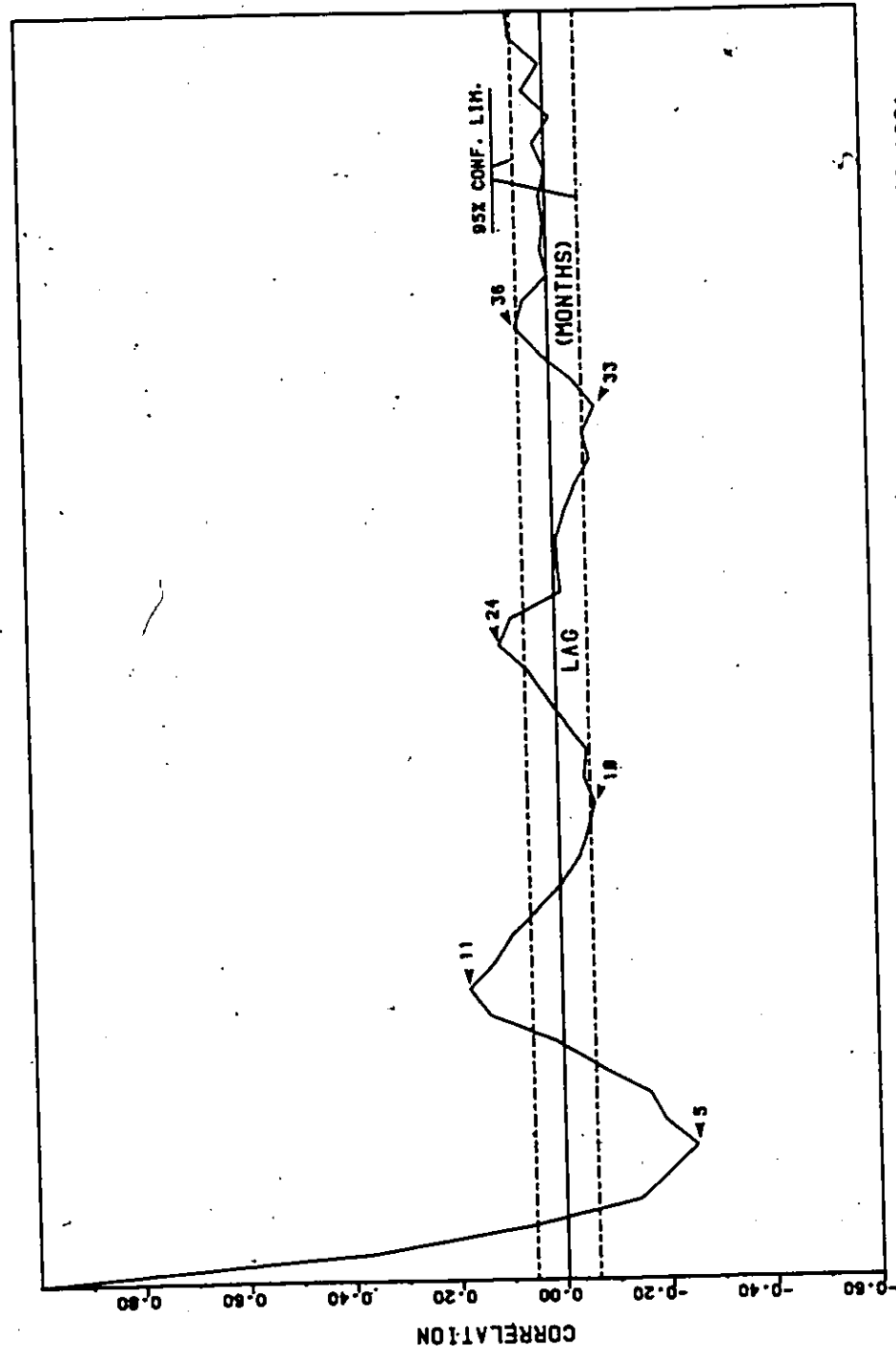


FIGURE 37: PARTIAL AUTOCORRELATIONS OF MONTHLY RAINFALL, OTTAWA CDA, 1890-1981

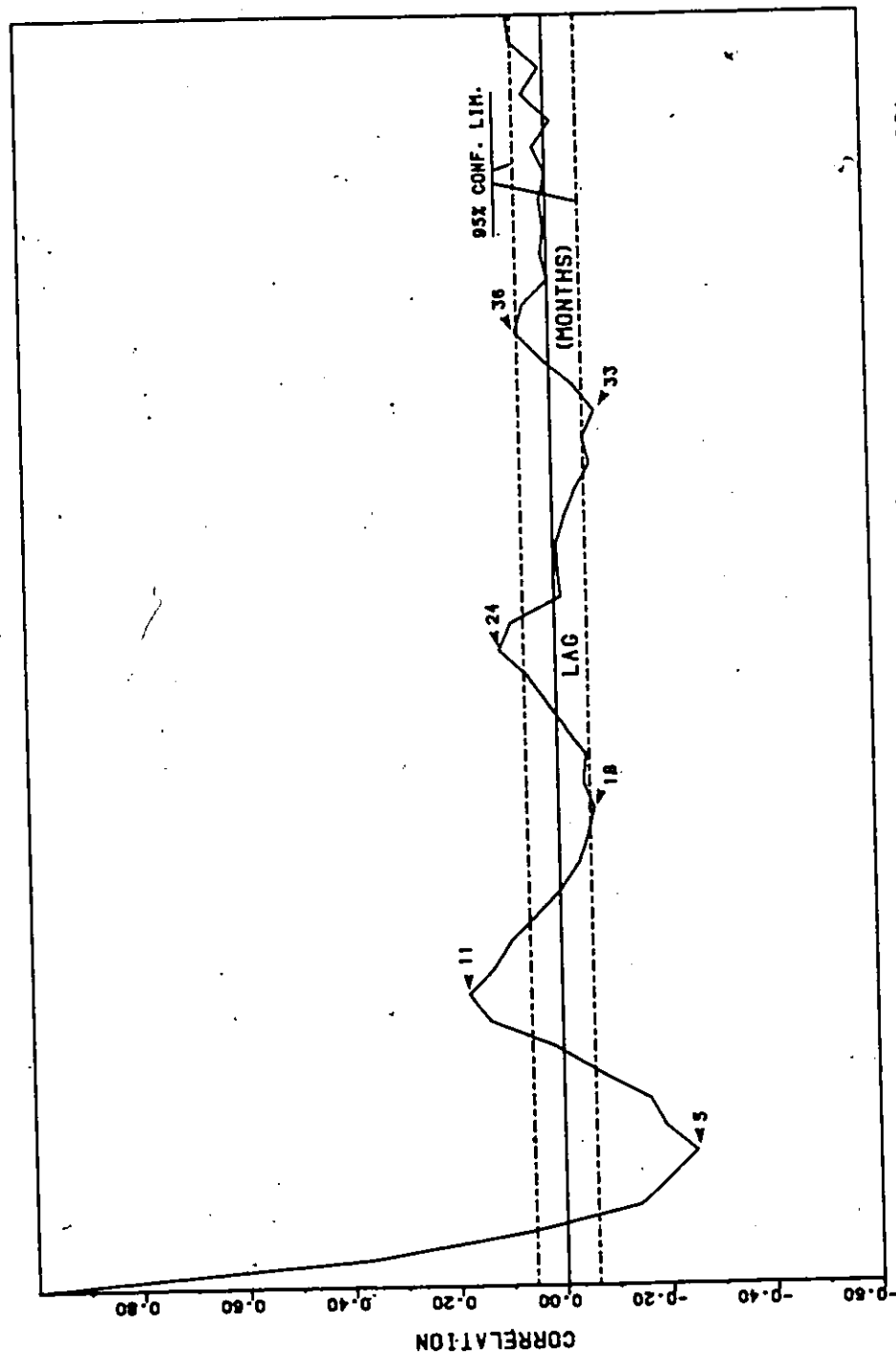


FIGURE 37: PARTIAL AUTOCORRELATIONS OF MONTHLY RAINFALL, OTTAWA CDA, 1890-1981

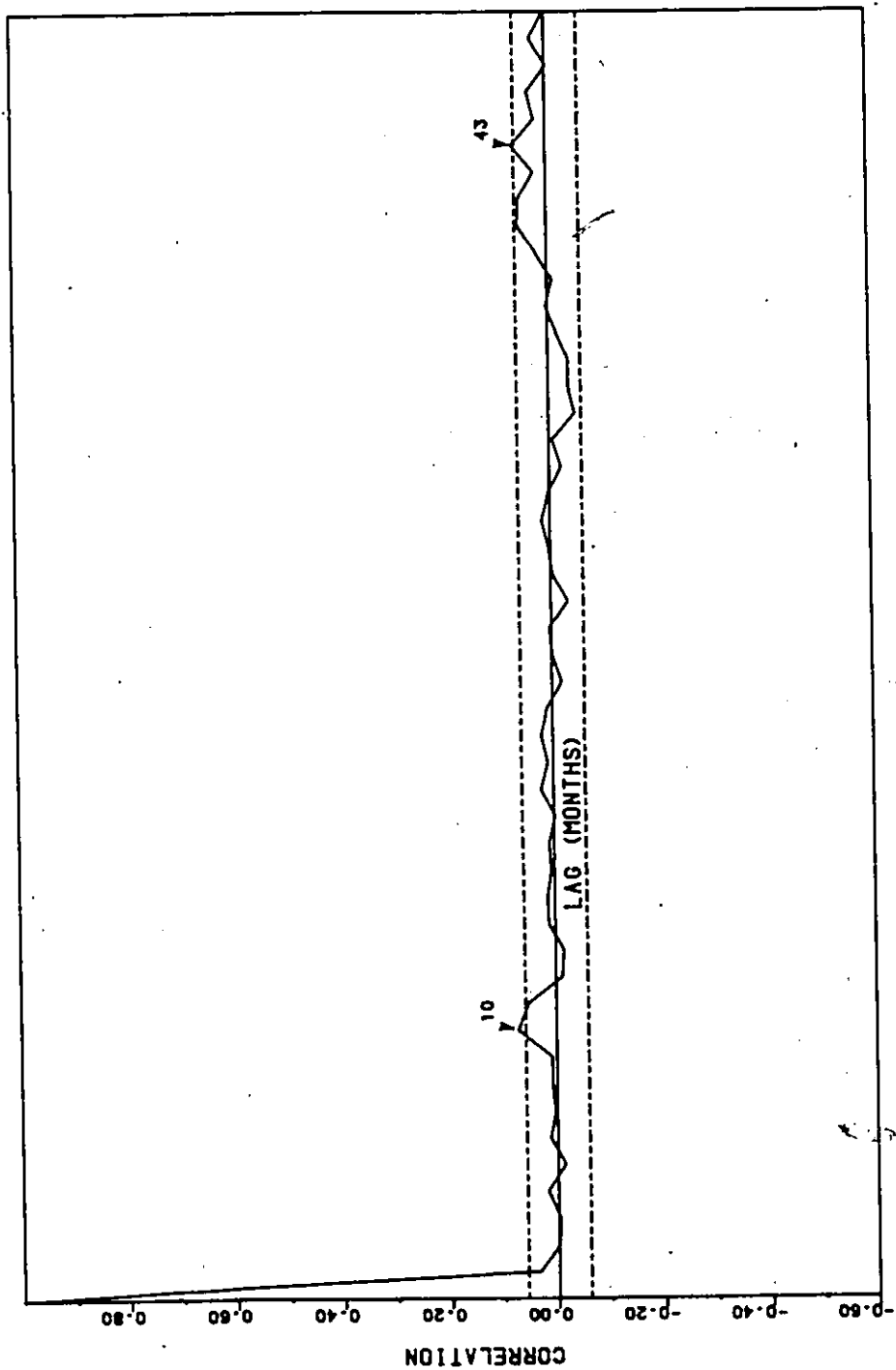


FIGURE 38: AUTOCORRELATIONS OF NORMALIZED MONTHLY RAINFALL, OTTAWA CDA, 1890-1981

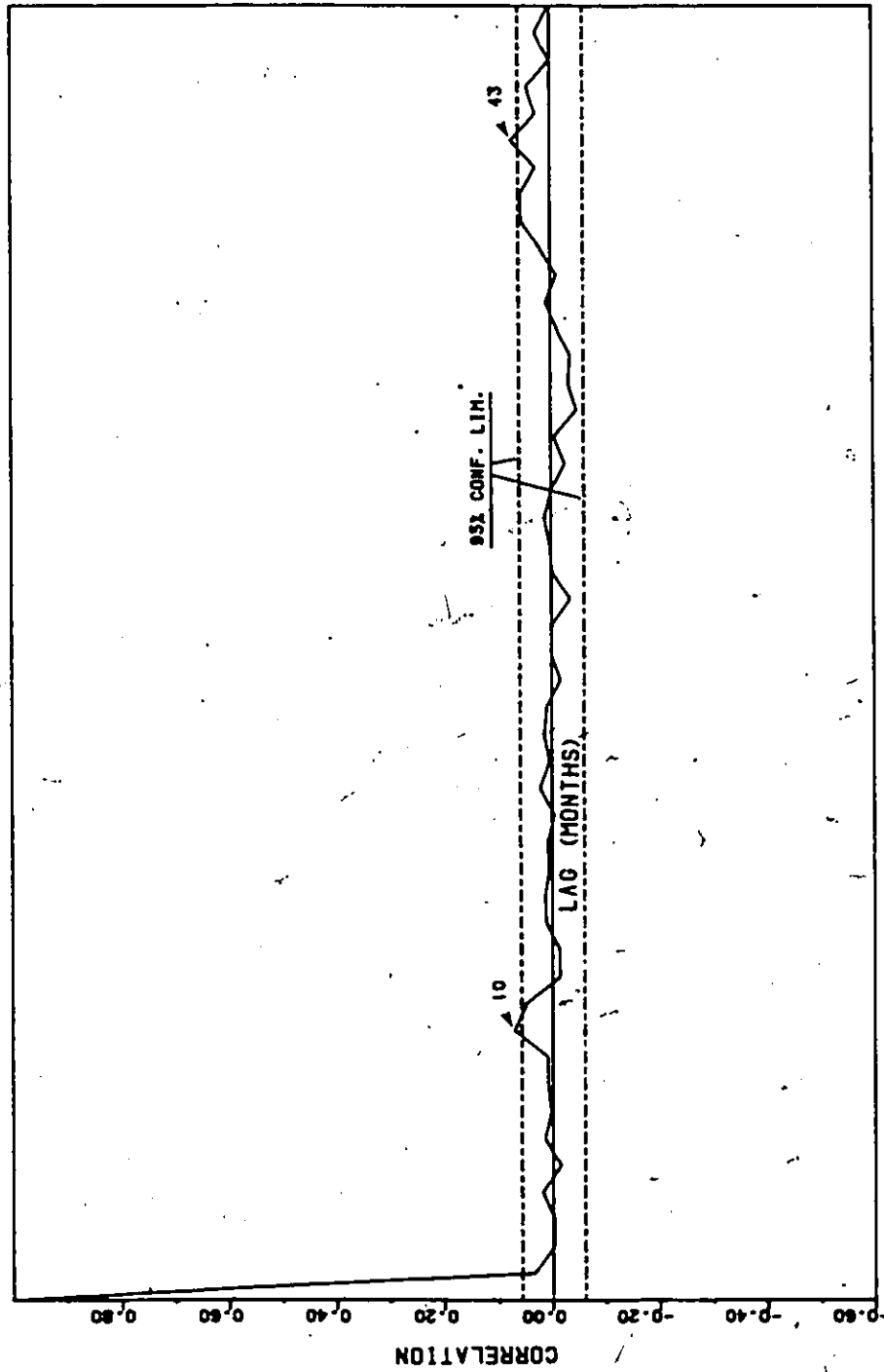


FIGURE 39: PARTIAL AUTOCORRELATIONS OF NORMALIZED MONTHLY RAINFALL, OTTAWA CDA, 1890-1981

any physical meaning and they were thus disregarded. In effect, the ACF and PACF truncate after lag zero, indicating white noise (see [24]). The result is that normalization produces a nearly random series and points to a model with at most lag-1 correlations as being appropriate for this monthly rainfall. Months are not strongly correlated with previous months or months at one month intervals. They appear to vary randomly about their monthly means.

The Thomas-Fiering Model is a lag-one, seasonally autoregressive model relating normalized data. Its use in this case seems reasonable although in respect to its use of one correlation term, it may even be an overspecification of the series. The generating equation has the form:

$$\left[\frac{q_{i,j} - u_j}{\sigma_j} \right] = \rho(j) \left[\frac{q_{i-1,j-1} - u_{j-1}}{\sigma_{j-1}} \right] + t_i \sqrt{1 - \rho^2(j)} \quad (6.1)$$

where

i is a sequential counter

j is a season counter

$\rho(j)$ is the correlation between seasons j and $j-1$

$q_{i,j}$ is the i th value generated and is in the j th season

σ_j is the standard deviation in the j th season

u_j is the mean value of the flows in the j th season

t_i is a random variable from some distribution.

which clearly shows the two parts:

1. Deterministic, relating one month's normalized value to the previous one by the lag - one correlation
2. Random, represented by t_1 .

Its more familiar form for computation purposes is:

$$q_{1,j} = u_j + \rho(j) \frac{\sigma_j}{\sigma_{j-1}} \left[q_{1-1,j-1} - u_{j-1} \right] + t_1 \sigma_j \sqrt{1 - \rho^2(j)} \quad (6.2)$$

The procedure for generating traces was similar to Burges [3]. For each trace, fifteen years of data were generated and discarded to be free of starting problems with the random generator and the initial value (taken as the seasonal mean). The random seed and this initial value were reset with each year of data generated. The trace was generated using the resultant random seed and the year-end value necessary for calculation of the value for the first month of the trace. This process was repeated until the required number of traces was generated.

6.2 CHOICE OF DISTRIBUTION

6.2.1 Histogram

The generation of data using a Markov sequence should preserve the distribution of the original data. This is accomplished by generating the random component of the model from a distribution that closely approximates the original. Klemes (p. 3 of [36]) in speaking of streamflows, says:

Given the usual length of record (40 years or less), it is hard to find a distribution model for

annual runoff that can be rejected on the customary 5% level of significance.

Although longer rainfall series are available, the distribution in any case still plays a part in the generation and a choice must be made on the best possible information. A histogram of all 92 years of Ottawa CDA monthly data is plotted in Figure 40 with a class interval of 25 mm. It shows a highly positively skewed distribution and suggests a Gamma-type distribution. If this were the case it would coincide with the work of others. Haan [22] says (p. 104):

The gamma distribution has been widely used in hydrology. Rainfall probabilities for durations of days, weeks, months and years have been estimated by the gamma distribution (four references follow).

6.2.2 Distributions Available

For the Thomas-Fiering lag-1 Markov generation model, four distributions are commonly used: Normal; Lognormal 2-parameter; Lognormal 3-parameter and; "like"-Gamma (Wilson-Hilferty). An explanation of how the generation was accomplished for each distribution is given in Appendix D.

6.2.3 Comparison

A comparison of the degree to which parameters of the input data are reproduced by the model using each distribution was carried out. Using parameters from 92 years of historical data, one thousand traces were generated, each of

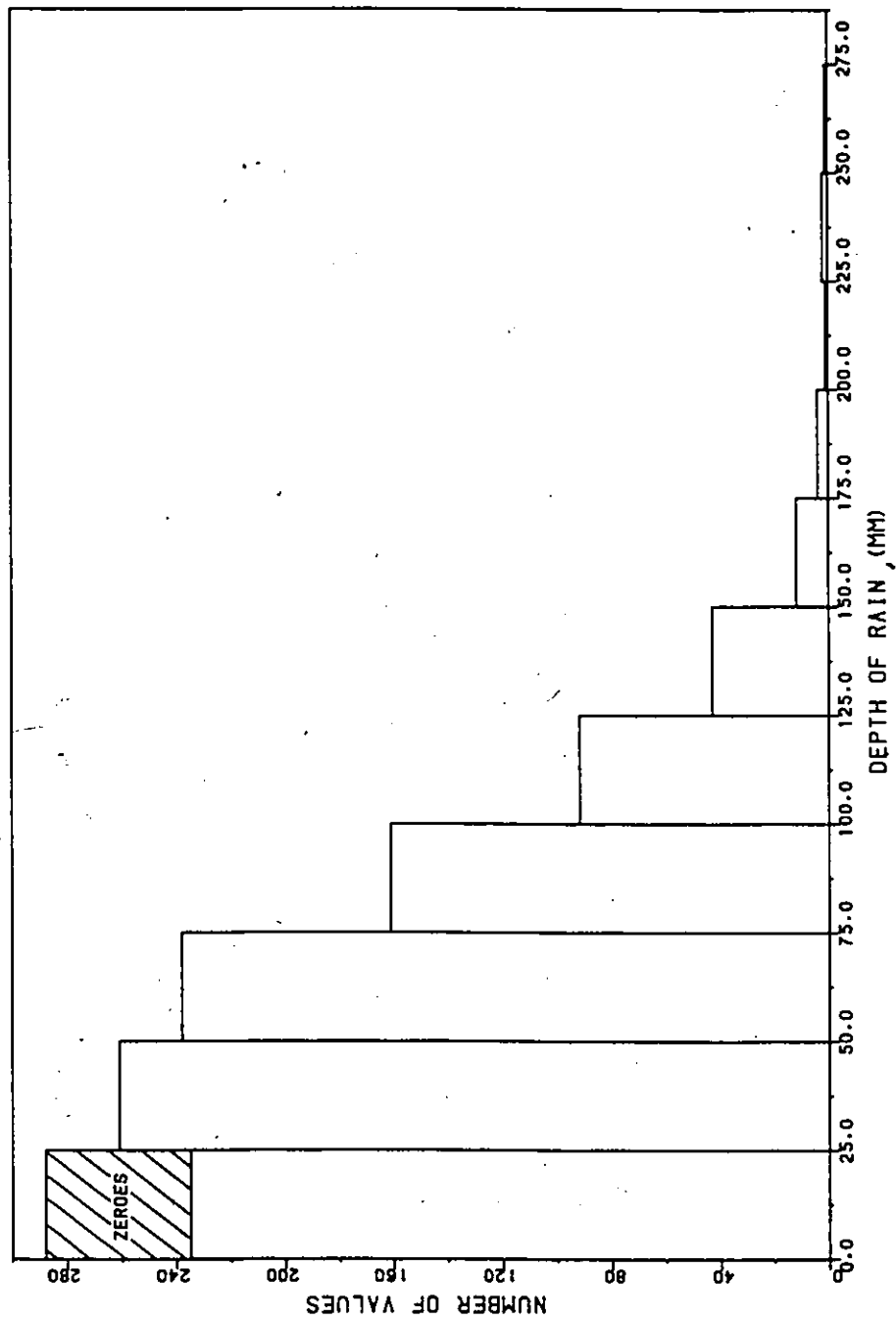


FIGURE 40: HISTOGRAM OF MONTHLY RAINFALL.
OTTAWA CDA RAIN, 1890-1981

40 years length and the parameters for each trace calculated by an unbiased estimation procedure presented by Stedinger and Taylor (p. 912 of [69]). The formulae for the procedure are given in the section "Stedinger and Taylor's Unbiased Estimators" of Appendix C. The estimates were averaged and a standard deviation of the estimates calculated. The parameters estimated are:

1. monthly means, coefficients of variation, coefficients of skew, seasonal serial correlations,
2. annual mean, coefficient of variation, coefficient of skew, correlation,
3. minimum annual,
4. overall minimum annual (no average taken).

An operational rating system was applied. The values calculated using each distribution were compared to the population values to see how well the parameters were preserved. The closest and the second closest to the original parameters as well as cases where the original value was more than one standard deviation away from the population value were noted. The results are presented in Table

4. The rating was determined by

$$(\text{NO. CLOSEST}) + (\text{NO. SECOND CLOSEST})/2 - (\text{NO. OUT OF RANGE})$$

(6.3)

The like-gamma distribution was a qualified winner. The 3-parameter models (LN3 and LG) reproduced CS better than the 2-parameter models, as expected, and LG did it slightly

TABLE 4

Rating Distribution Preservation of Input Parameters

Stedinger and Taylor Method
 1000 Traces, 40-year Data,
 Parameters from Ottawa CDA, Rain, 1890-1981

	NORMAL				LIKE GAMMA				LN2				LN3			
	1	2	X	PTS	1	2	X	PTS	1	2	X	PTS	1	2	X	PTS
Means	3		2	1	2	8	1	5	9	2	1	9		4	1	1.
CV	2		4	-2	10	1		10.5		3		1.5	1	9		5.5
Corr.	4			4	3	-4		5	5	3		6.5	1	6		4
CS	1		8	-7	7	6		10					5	7		8.5
TOTALS																
w/o CS	9		6	3	15	13	1	20.5	14	8	1	17	2	19	1	10.5
w CS	10		14	-4	22	19	1	30.5	14	8	1	17	7	26	1	19

Headings: 1 - no. of values closest to original
 2 - no. of values second closest
 X - no. of values more than 1 std. devn. from original
 PTS - rating = firsts + seconds/2 - X

better than LN3. If skew were not considered, the LG had a higher overall rating than all the others but was only slightly better than LN2 and was beaten in "seconds" by LN3. Considering skew, it was more clearly the winner with the highest firsts and points and lowest number out of range, but it still came second in "seconds" to LN3.

The effect of the different distributions on storage is discussed in the next section.

6.2.4 Conclusion

In conclusion, for models for which skew is not important, the LN2 is nearly as good as or better than 3-parameter models but where skew is important, LG is the best of models tested. Thus, while LG is not able to reproduce all of the statistics of the original series consistently better than the other distributions, its overall performance is the best of the distributions tested. With respect to computational ease, LG and LN2 are similar.

It is notable that while the average of all minimum annual values is higher than the original data's minimum annual, all of the distributions tested showed that minimum years can be produced that are considerably lower than the historical series. This is of considerable importance in estimating the storage required as larger storages than the historical value could possibly be produced by these low years.

6.3 CALCULATION OF STORAGE CURVES USING SYNTHETIC DATA

6.3.1 Overview

Programme CISTERN read in data parameters, generated a required number of traces of a given length, with the same number of seasons as the data. It then calculated the storage for each demand level chosen, fitted the storage values to an EV1 distribution and calculated the value for a given certainty level. Each part of the calculation is considered separately below.

6.3.2 Choice of Points to Be Calculated

An unsuccessful search for a functional relationship between non-dimensionalized demand and storage for special cases was undertaken. Instead of this, two points were chosen as representing upper and lower useful values in the Demand/Storage/Reliability curve. They were chosen on the following basis:

1. In design, the conservative case is to overestimate the storage.
2. Demand for the year is not expected to be less than one average month's inflow. That is, D/AR is no less than 0.0833.
3. Due to rapidly increasing storage at higher demands, it will seldom be feasible to increase demand above 0.9 of yearly input.
4. A line drawn between these two points on log-log plots overestimates the storage.

Thus a line drawn from $(0.0833, S^*(0.0833))$ to $(0.9, S^*(0.09))$ will produce a conservative estimate for design purposes of required storage over that range of demand. The amount of overestimation depends on the particular data used. The investigations below concentrated on the storage required for these two demands.

6.3.3 Parameters

Seasonal means, coefficients of variance and lag-one correlations were read in for all cases and, in addition, coefficients of skew for LN3 and LG. Suitable generation parameters were calculated for the chosen distribution. It was found that the seasonal means could be replaced by the monthly fractions of the annual mean with minor resultant changes in the output. Theoretically, no changes should occur.

6.3.4 Length of Trace

A standard length of 40 years was used for tests reported in this thesis, for the previously presented reasons. However, the model was written so that it could be set for any length up to 100 years.

6.3.5 Number of Traces

Burges [3] showed that 1000 traces of 40 year length will define the distribution of storage. For this reason and because 1000 traces produces a set of data requiring a sizeable storage and considerable computing time, 1000 traces were generated and used to calculate storage values for each case considered in the thesis. The programme had the capability to be set so that any number of traces up to 1000 could be generated.

6.3.6 Storage Value Determination

6.3.6.1 Calculation for Each Trace

It is noted in the Demand/Storage curves that, while storage values range over the full interval of [0.01, 1.], the demand range is more restricted, especially above 0.9. This is the reason that the curve was calculated by assuming values of S'' and calculating D'' . However, if the range of D'' is restricted to [0.01, 0.9], it is possible to calculate S'' given D'' by a similar method.

The subroutine to do this was written and incorporated in CISTERN as SBYR.

6.3.6.2 Distribution of Storage Values

Burges [3] presents a heuristic argument that the distribution of calculated storage values produced by a storage calculation similar to the mass curve (sequent peak) is EV1 (Gumbel). This was assumed to apply in the present case.

The probability distribution function is defined as

$$f(x) = \exp(-\exp(-y)) , y = a(x-U) \quad (6.4)$$

Following Yevjevich's suggestion (p. 154 of [78]) that the skew of the distribution (a constant 1.29857) is sufficiently high that the parameters a and U should be estimated by maximum likelihood methods, a subroutine EV1 was written to fit the 1000 storage values for each demand level by B.F. Kimball's Maximum Likelihood procedure (pp 231-2 of [20]).

For a sample x_i , $i=1, \dots, N$, the Maximum Likelihood equations are:

$$e^{aU} \sum e^{-ax_i} = N \quad (6.5)$$

$$\frac{\sum x_i e^{-ax_i}}{\sum e^{-ax_i}} + \frac{1}{a} = u \quad (6.6)$$

where

u is the mean of the x_i

N is the number in the sample

$$\sum = \sum_{i=1}^N$$

The second equation is independent of U so that it, in the form

$$\frac{1}{a} = u - \frac{\sum x_i e^{-ax_i}}{\sum e^{-ax_i}} \quad (6.6a)$$

is solved iteratively for a by putting the best estimate into the right side and obtaining a new value. An error of 0.1% in a was used to stop the iteration. Then, U is calculated from the first equation. The initial estimate for a was found from

$$a = \frac{\pi}{\sigma\sqrt{6}} \quad (6.7)$$

where σ is the standard deviation of the storage values. This was obtained by the method of moments estimates (p. 227

of [20]), (p. 8-16 of [7]). When a and U had been determined, a storage value could then be calculated for a given level of certainty:

In operating the algorithm, it was found that it was neither as stable nor as rapidly converging as Kimball suggested. A single out of range value in 1000 would upset the algorithm and cause it to diverge. To correct this, a visual check was made of any non-converging data and outliers were removed. Convergence was accelerated by averaging present and previous estimates.

6.3.6.3 Level of Certainty

When using a Gumbel distribution, it is common practice to relate the level of certainty to a return period which means the period within which the chosen value was equalled or exceeded in the data.

If C is the certainty of some value S read from the Gumbel distribution, it means that C of the values are less than S . The probability that the storage will be greater than or equal to S is $1-C$. Thus the return period is

$$T = 1/(1-C). \quad (6.8)$$

Traditionally, this is given as the number of "years" but Chow also calls it "trials" (p. 9-59 of [7]) or "cases" (p. 8-22) which is better terminology in this case.

Because a single storage value is obtained from 40 years of data, it is incorrect to say that a storage value with a

certainty of 0.99 has a 100 year return period. Rather, it should be said that it has a return period of 100 trials (or 4000 years in this case). It therefore means that at least one in one hundred sets of 40-year period will require a storage larger than the determined value.

To choose the level of certainty, consider the risk factor. It is defined as the probability that the required storage will exceed S at least once in n trials.

$$\text{Risk} = 1 - c^n \quad (6.9)$$

In the medium-term, the risk of failure in 100 years (i.e. 2.5 trials) is a reasonable level to use as a standard for a rainwater collector. For 40-year cycles, the resulting calculations are shown in Table 5.

TABLE 5

Return Period and Risk

Return Period years	trials	Certainty $C = 1 - 1/T$	Risk in 100 years $1 - C^{2.5}$
40	1	0.	1.
100	2.5	.6	.721
200	5	.8	.428
400	10	.9	.232
600	15	.933	.158
800	20	.95	.120
1000	25	.96	.097
2000	50	.98	.049
4000	100	.99	.025

Since the demand for water from rainwater collectors is highly elastic ([26], [55]) and supply is seasonal, reasonably high risk can be accepted. Failure can be reduced by conservation measures and is usually of, at most, several months duration. Moreover, failure is not catastrophic as it would be in the case of a breached dam and should not adversely affect the future operation of the system.

For these reasons, a 20% risk in 100 years was chosen as the level of certainty. This corresponds to a certainty of 0.915 and represents a return period of 11.7 trials or 468 years. A test of this level is made later on historical data.

6.4 TESTS

6.4.1 Distribution

The data for 40 years Ottawa CDA 1942-1981 were analysed and suitable parameters calculated and fed into the synthetic data programme. The Demand/Storage/Reliability lines for each of the four distributions were calculated and are presented in Figure 41 along with the 99% reliability historical data line. A similar procedure was followed for data for 1890-1929 to obtain Figure 42. Figure 41 shows that at the 0.915 certainty level, the LG and LN3 points are nearly coincident but are above the historical line. LN3 may be slightly above LG. The LN2 points are generally below the historical line. The normal points were above the

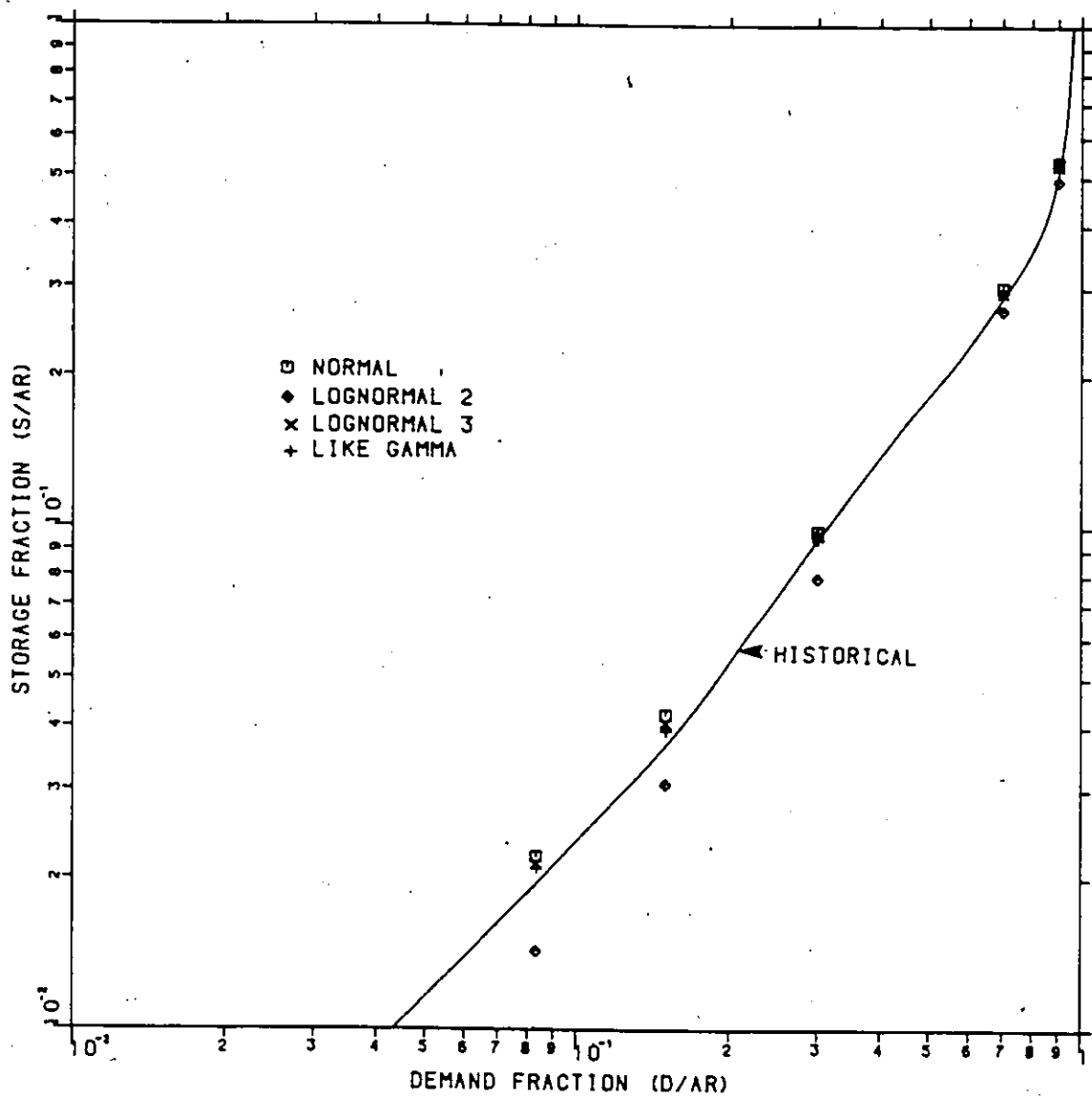


FIGURE 41: COMPARISON OF HISTORICAL AND SYNTHETIC STORAGES.
 RAIN, OTTAWA CDA, JAN 1942 - DEC 1981
 99% RELIABILITY, .915 CERTAINTY

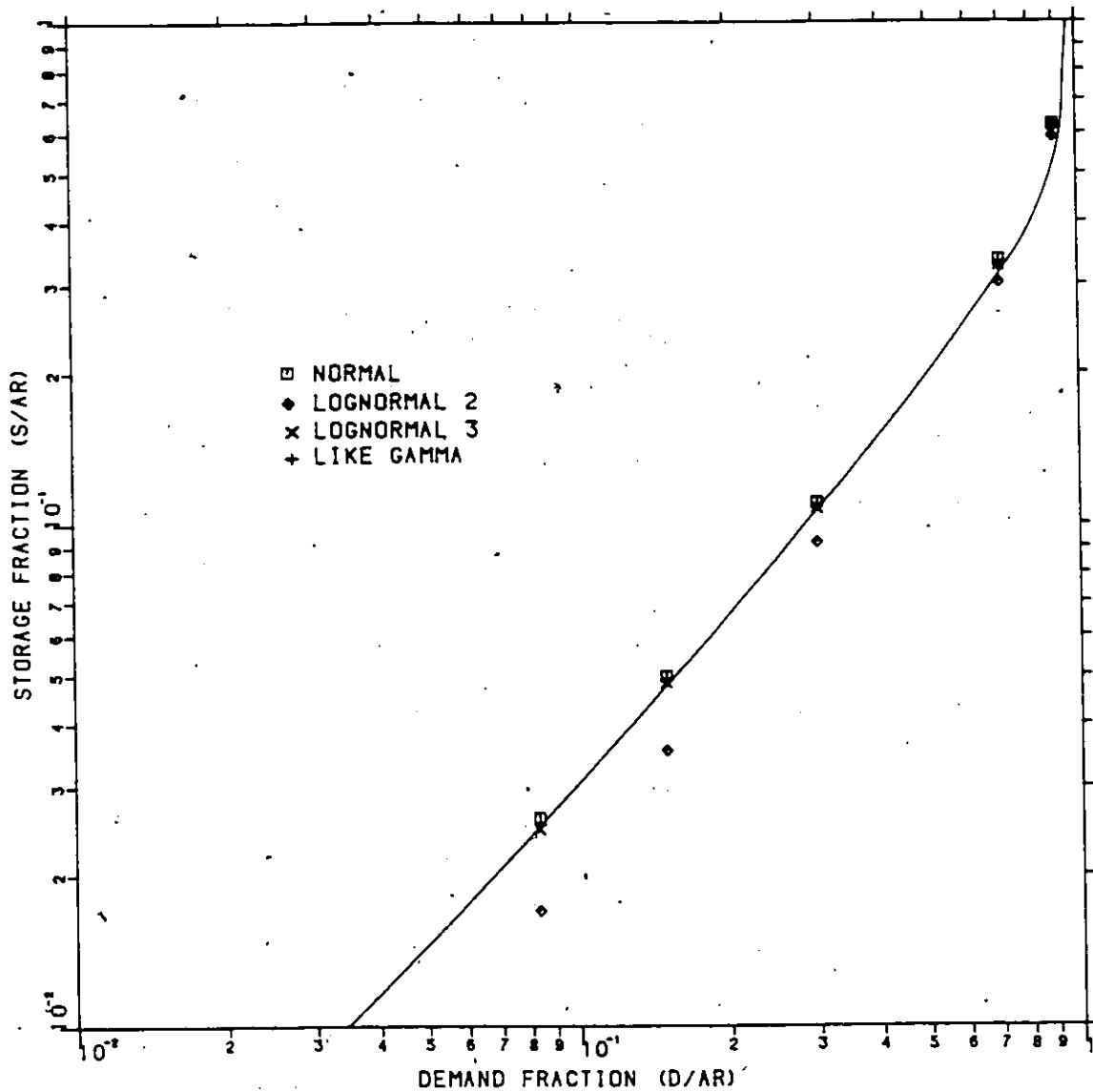


FIGURE 42: COMPARISON OF HISTORICAL AND SYNTHETIC STORAGES.
 RAIN, OTTAWA CDA, JAN 1890 - DEC 1929
 99% RELIABILITY, .915 CERTAINTY

LN3 and LG points but still within 20% of the historical storage values. In Figure 42, a similar pattern is evident although the LG points are now above the LN3 ones. The Normal distribution still produces the largest storages.

From this analysis, it is seen that both 3-parameter distributions (LG and LN3) give reasonable approximations to the historical data values of storage required at the 0.915 certainty level. There is little to distinguish the two. Coupling this reproduction of storage with the analysis of reproducibility of data parameters, the LG distribution was chosen for data generation for further studies because it reproduces the statistical parameters best and produces storages that are a reasonable approximation to the historical data values.

Next, forty-year sequences were generated using the parameters for the full 92 years of data. The placement of distribution lines in Figure 43 shows a similar pattern to Figure 41.

Next, in Figure 44, outputs from 40 years of synthetic data for LG based on 92 year population parameter estimates are compared to outputs from synthetic data using parameters estimated from the periods 1890-1929, 1916-1955, and 1942-1981. The storages based on the larger population are not always greater than those generated with parameters estimated from sub-populations. It would be expected that more data, i.e. a longer series, would include and reflect

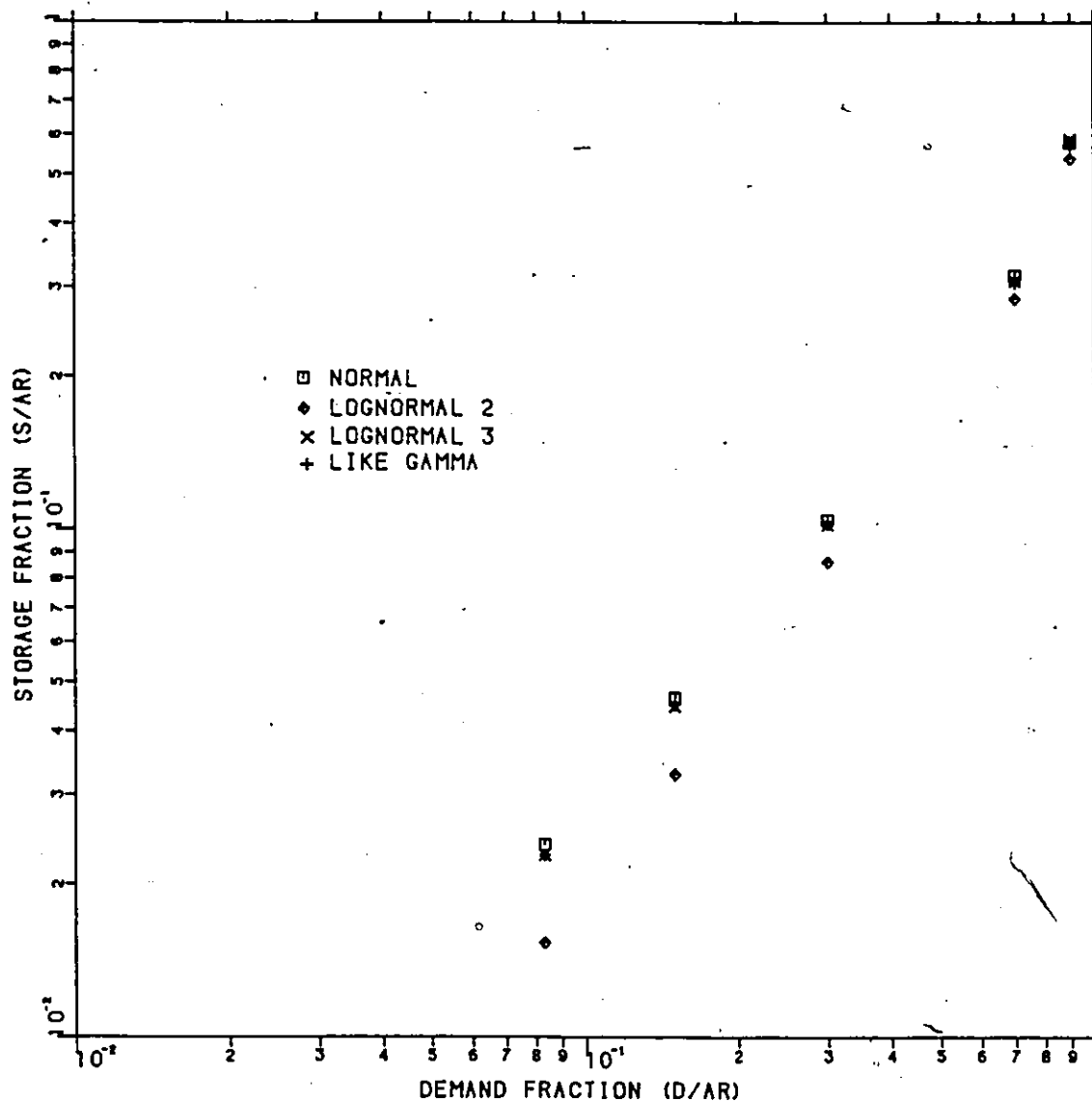


FIGURE 43: COMPARISON OF SYNTHETIC STORAGES OF
 40 YRS OF DATA GENERATED WITH 92-YR PARAMETERS.
 RAIN, OTTAWA CDA, JAN 1890 - DEC 1981
 99% RELIABILITY, .915 CERTAINTY

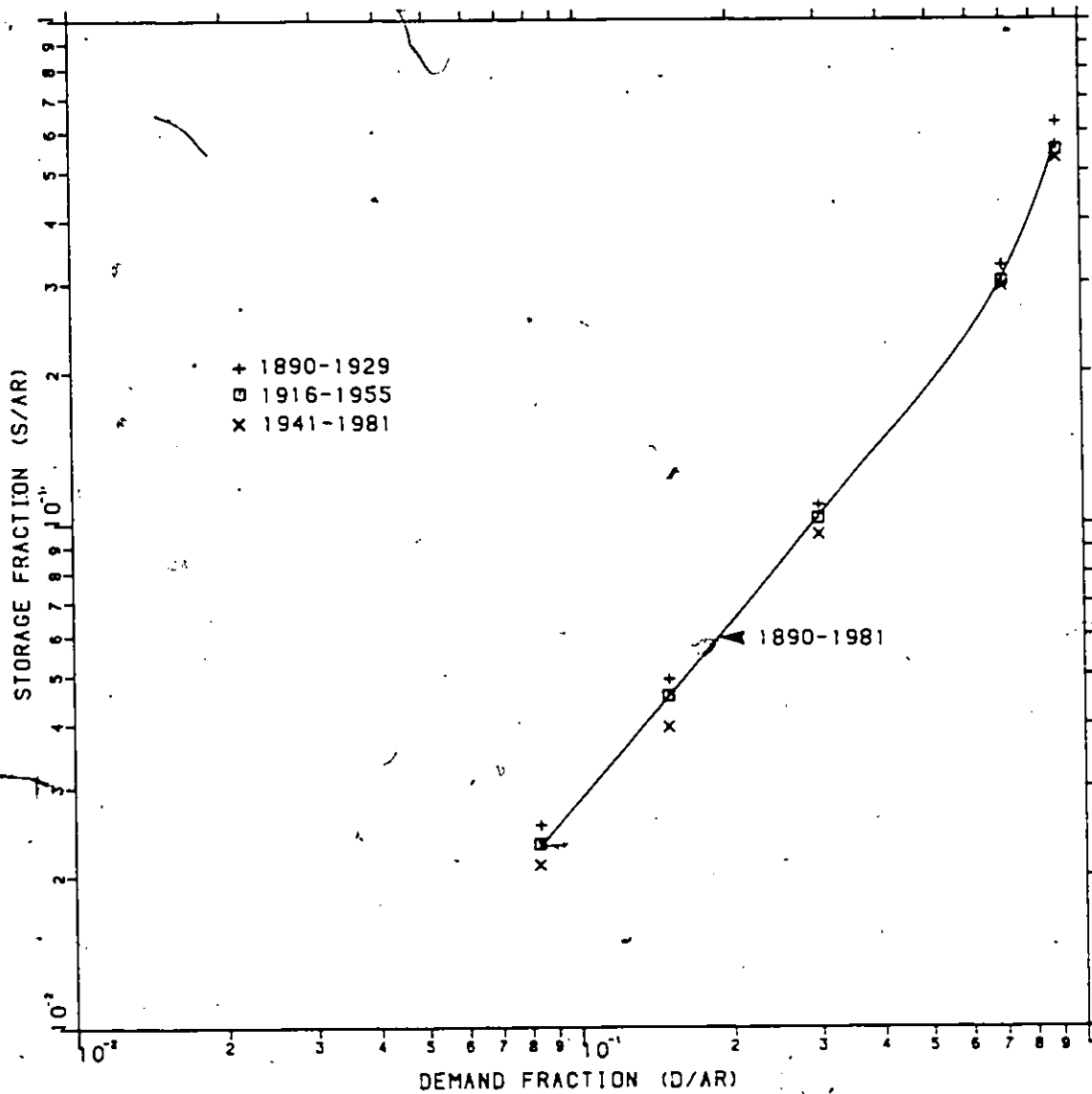


FIG. 44: COMP. OF 40 YRS OF DATA GENERATED
WITH 92-YR & 40-YR PARAMETERS.
RAIN, OTTAWA CDA.
LIKE GAMMA, 99% RELIABILITY, .915 CERTAINTY

any severe periods. However, some damping of severity appears to occur due to the parameter estimation process.

6.4.2 Certainty

The assumption of a certainty level of 0.915 was verified. The levels for the historical cases of 1890-1929 and 1942-81 were calculated using Like Gamma with parameters estimated using the same data. The historical values and the corresponding levels of Certainty for that value are given in Tables 6 and 7.

TABLE 6

Ottawa CDA 1890-1929 Based on Like Gamma

Demand	Historical (Fig. 41)	Certainty of Hist.	S(.915)	S(.85)
0.0833	0.025	0.902	0.0252 (+0.8%)	0.0243 (-2.8%)
0.15	0.0485	0.899	0.0490 (+1.0%)	0.0473 (-2.5%)
0.30	0.107	0.886	0.1086 (+1.5%)	0.1055 (-1.4%)
0.70	0.314	0.809	0.3241 (+3.2%)	0.3170 (+1.0%)
0.90	0.56	0.757	0.6230 (11.3%)	0.5897 (+5.3%)
Average of absolute % errors			3.6	2.6

The average certainty of the historical values is 0.85 (Risk of 33% in 100 years) in both cases. The storages for certainties of 0.915 and 0.85 are presented above as well as the percentage differences from the historical. The average of the absolute error percentages was calculated and it

TABLE 7

Ottawa CDA 1942-1981 Based on Like Gamma

Demand	Historical (Fig. 42)	Certainty of Hist.	S(.915)	S(.85)
0.0833	0.0198	0.644	0.0210 (+6.0%)	0.0205 (+3.5%)
0.15	0.0382	0.811	0.0394 (+3.1%)	0.0386 (+1.0%)
0.30	0.096	0.933	0.0949 (-1.1%)	0.0923 (-3.9%)
0.70	0.293	0.901	0.2946 (-0.5%)	0.2885 (-1.5%)
0.90	0.55	0.949	0.5303 (-3.6%)	0.5081 (-7.6%)
Average of absolute % errors			2.8	3.5

shows that neither value is clearly better in all cases. Therefore, the conservative estimate was taken and the certainty was taken to be 0.915 as before.

6.5 SUMMARY

The computer programme CISTERN was written to generate data for and analyse storage values from the storage calculation developed in the previous Chapter. It was written generally so that generated data distribution, length of trace, number of traces, and level of certainty could be easily set.

The Thomas-Fiering model is expected to be adequate to generate sets of data for testing purposes. Since seasonal serial correlations are small, it may represent an overspecification of the historical series.

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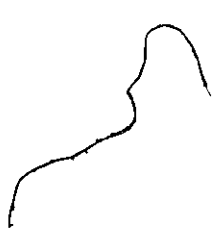
6.5 SUMMARY

The computer programme CISTERN was written to generate data for and analyse storage values from the storage calculation developed in the previous Chapter. It was written generally so that generated data distribution, length of trace, number of traces, and level of certainty could be easily set.

The Thomas-Fiering model is expected to be adequate to generate sets of data for testing purposes. Since seasonal serial correlations are small, it may represent an overspecification of the historical series.

A comparison of the ability of four different distributions which may be part of this generation model showed that no single distribution would reproduce exactly the parameters of the historical data or even reproduce them consistently better than all the others. However, the best performer was found to be the Like-Gamma, even when skew is not considered in the evaluation. Like-Gamma also calculated the storage values well. Based on its reproduction of statistical parameters and storages, it was chosen as the distribution for further studies.

The storage value used to typify the parameters fed into the generation / storage model was determined by a level of risk of failure of 20% in 100 years, which was chosen for physical reasons. The average risk of historical data was found on the average to be above this but 20% was deemed adequate in order to estimate the storage at both upper and lower values of demand. The lower risk leads to a higher storage value for a given demand.



Chapter VII

STUDY OF EFFECTS OF MAJOR INPUT PARAMETERS ON STORAGE

In this chapter, the monthly rainfall and storage models were combined into one programme. The statistical characteristics, and hence the pattern, of the rainfall regime were varied one by one and the effects on the required storage were noted.

7.1 REVIEW OF MODEL

The synthetic hydrology and storage model used in investigations in this chapter had the following characteristics:

1. Storage Calculation

- a) Conservative (YAS) Calculation
- b) monthly data
- c) Reliability based on volume supplied
- d) 99% reliability level
- e) no rationing
- f) no stocking
- g) WARMUP subroutine used to calculate initial storage

2. Rainfall Model

- a) Thomas-Fiering Lag-1 Model
- b) Like-Gamma Distribution

- c) 1000 traces generated
- d) each trace is 40 years long
- e) storage values fitted to EVI distribution by Maximum Likelihood
- f) 0.915 certainty level in storage
- g) calculations made for demand fractions of 0.0833 and 0.9.

7.2 INPUT DATA

All input parameters were non-dimensional. Since the resultant graph is dimensionless, it is independent of the scale of the input seasonal means and hence the seasonal means can be normalized by dividing by the annual mean rainfall.

Other input parameters to the generation model are coefficient of variance, seasonal correlation and coefficient of skew for each season. Thus, the generation model is independent of the historical data except for the assumption of a like-Gamma distribution.

7.3 SCOPE OF INVESTIGATION

The model was run more than 131 times for various combinations of input parameters. Skew was investigated in 5 cases, seasonal serial correlation in 11, monthly means in 55 and monthly coefficient of variation in 60 cases. Unless otherwise stated, the values of monthly parameters were those determined from Ottawa CDA rain 1890-1981 data.

As a basis of comparison, the model was run with all historical parameters to obtain the historically-derived storages:

Demand Fraction	Storage Fraction
0.0833	0.0228
0.9	0.5743

7.4 SKEW AND CORRELATION

7.4.1 Skew

Because of a lack of a discernible pattern in monthly coefficients of skew, these were taken to be the same for all months. The results of 5 runs for values of Coefficient of Skew of 0.1, 0.5, 1.0, 1.5, 2.0 are plotted in Figure 45 as a fraction of the historical data value.

The effect of setting all skews to a single constant value was determined by the values of storage at the skew value of 0.8082. The difference is $\pm 1.5\%$ of historically-derived values with $D'' = 0.0833$ being above the historical and $D'' = 0.9$ below. The conclusion is that there is no great difference between the historical data value of storage and the value derived with CS constant for all seasons. Thus, a single skew value can be estimated from the complete population and its value used. CS for the monthly data was 0.8082 and 0.8 was used in later examinations.

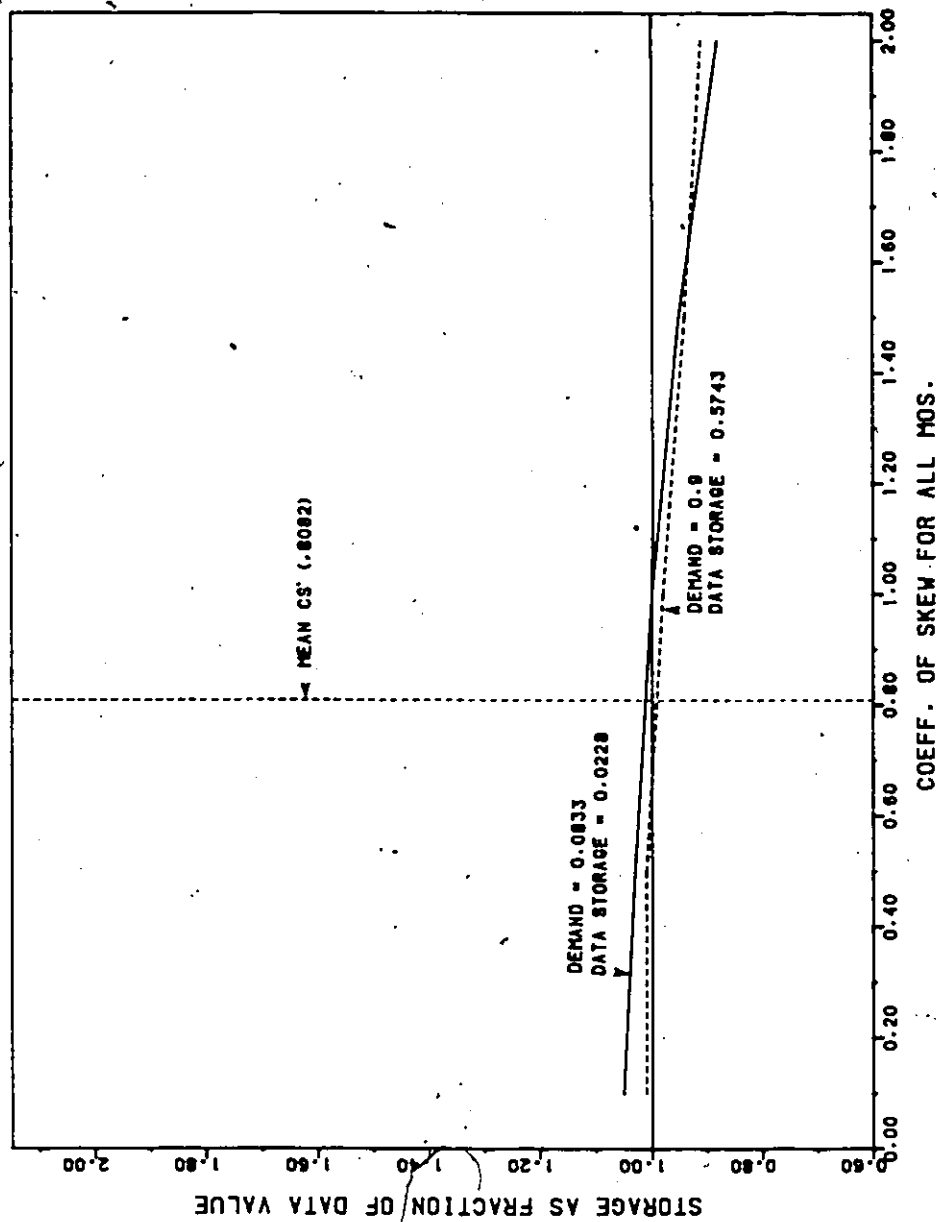


FIG. 45: EFFECT OF CONSTANT MONTHLY SKEW ON STORAGE.
OTTAWA CDA. RAIN. 1890-1981.

The variation in storage was greater with a demand of 0.0833 where it varied from 0.88 to 1.05 of the historically-derived value, compared to the case of demand of 0.9 where the storage varied only from 0.91 to 1.01 of the historically-derived value. Overall, storage is not very sensitive to skew in either demand case. The trend, however, is that increased skew gives lower required storage.

7.4.2 Correlation

Seasonal serial correlation was treated in a similar manner. Since all values were not significant at 95% and no pattern in the monthly values was noted, the correlations for all months were assumed constant and the values were varied from -0.5 to 0.5. The results are plotted in Figure 46, again as a fraction of the historically-derived value.

Correlation has a significant effect on storage. The general trend is that increasing correlation means more storage. Correlation varying within the bounds of the 95% significance level alone causes storage to vary from 10-15% ($D'' = 0.0833$) to 20-40% ($D'' = 0.9$). Greater variation is evident outside of that range.

Since there is such a difference among values for correlation within the significance limits, the effect may be due to the assumption that correlation is constant for all months. However, in both demand cases, the storage for $p(j) =$

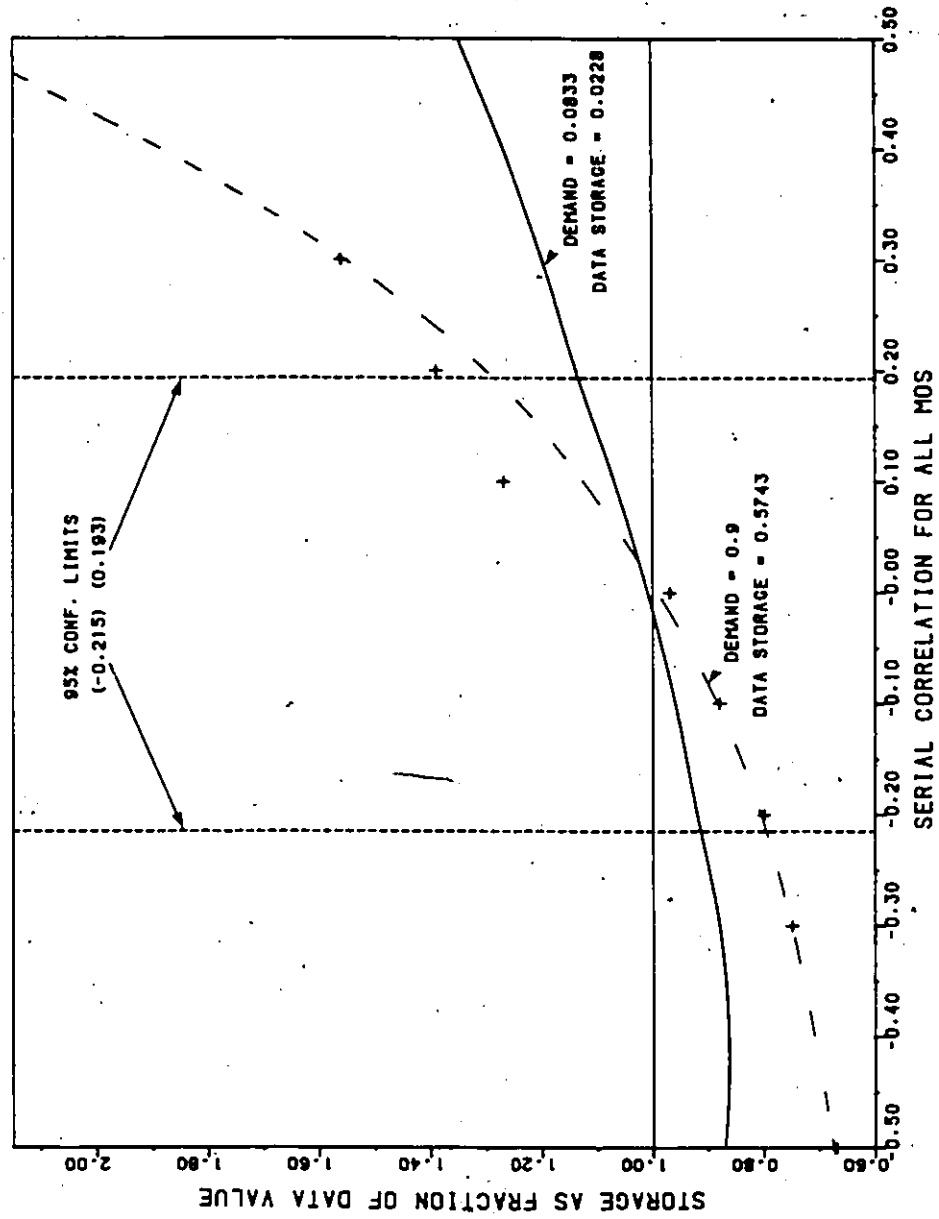


FIG. 46: EFFECT OF CONSTANT MONTHLY CORRELATION ON STORAGE.
OTTAWA CDA, RAIN, 1890-1981.

0.0 was approximately equal to the historically-derived value. It appears that seasonal serial correlation is a statistic with a definite distribution. Setting the correlation values in the model may be equivalent to setting the mean of the distribution. For example, setting the correlation to 0.1 may not mean that the value of the correlation is 0.1 but rather that it is 0.1 with some confidence. An analogy with confidence limits about 0 correlation might be made. No further studies of this particular hypothesis were carried out.

7.4.3 Effect of Constant Skew and Correlation

Later models assume correlation and CS to be constant for all seasons and equal to 0.0 and 0.8 respectively. The effects of these changes on the storage are shown in Table 8.

There is a 1.8% increase in storage for a demand of 0.0833 with the changes in correlation and CS having a similar effect. However, in the case of demand of 0.9, there is a 3.6% decrease in storage, with the correlation change having a greater effect than the change in CS.

TABLE 8

Storage Values for $\rho(j) = 0.0$, $CS = 0.8$

<u>Demand = 0.0833</u>		
	<u>CS from data</u>	<u>CS = 0.8</u>
$\rho(j)$ from data	0.0228	0.0231
$\rho(j) = 0.0$	0.0231	0.0232
<u>Demand = 0.9</u>		
	<u>CS from data</u>	<u>CS = 0.8</u>
$\rho(j)$ from data	0.5743	0.5686
$\rho(j) = 0.0$	0.5577	0.5534

7.5 PATTERNS OF MONTHLY MEANS

There are two features of the monthly means pattern that were studied: the length of the period with low rainfall and; the severity of the low rainfall. These were handled by assuming a two-season (wet/dry) model with a certain number of consecutive months with "low" values and the rest of the year with "high". Severity was quantified by the ratio of the rainfall in a "high" month to that in a "low" month.

The model was run for 1 to 11 low months and high/low ratios of 1.5, 3., 5., 10., 20. Correlation was set at 0.0 and CS was set at 0.8 for all months. Coefficient of variation was set at 0.5 if the mean fraction was above 0.0833 (the average monthly value) and 1.0 if the mean fraction was

below this. These values for CV were determined by a visual examination of the historical data parameters (see Figure 5). The results are presented in Figures 47 and 48 for demands of 0.0833 and 0.9 respectively. The basis of comparison was the historically-derived storage fraction values as before as well as the demand level.

For a demand of 0.0833, the storage value varies 70% of the historically-derived storage fraction and is increased by both increasing severity and increasing number of "low" months, but the effect is greatest at high severity levels (above 10.) where storage reaches a maximum with 7 low months. Severity has its greatest effect with 4 to 9 low months where the storage may increase 35 to 40% when severity increases from 1.5 to 20. but in other cases, the increase is only about 3% (1 and 11 months).

For demand of 0.9, the effects are much more dramatic with storage values varying over 375% of the historic parameter value. For up to 7 low months, the severity has little or no effect on storage. Any increase due to severity is effectively confined to severities below 5. For greater than 7 low months, increasing either factor results in higher storage.

In summary then, over the ranges of the parameters studied, the number of low months (i.e. length of the dry season) has a greater effect on the storage required than does the severity (high/low ratio). For fewer than 4 low

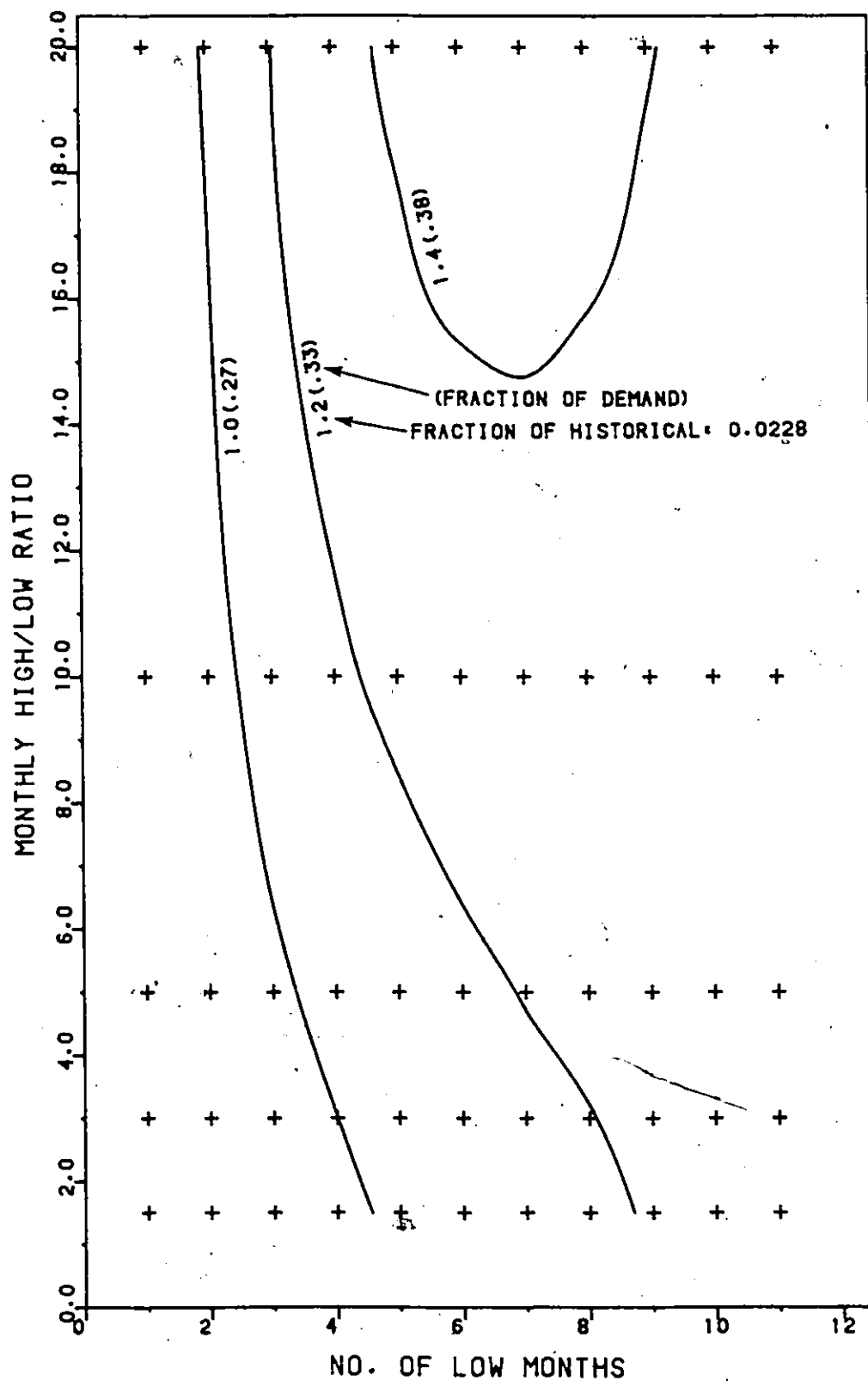


FIG. 47: EFFECT OF NO. OF LOW MONTHS AND
HIGH/LOW RATIO ON STORAGE.
DEMAND = 0.0833

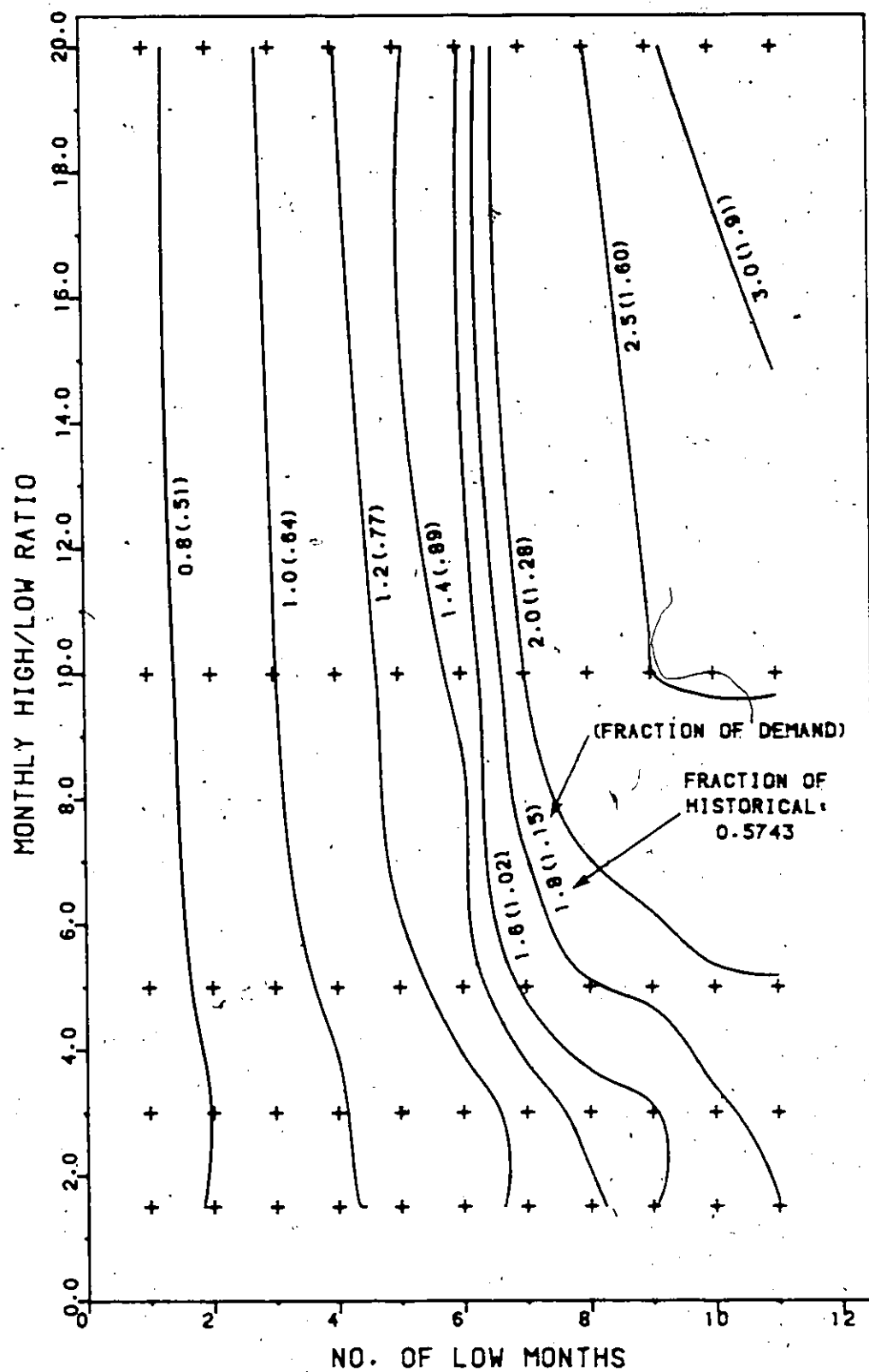


FIG. 48: EFFECT OF NO. OF LOW MONTHS AND HIGH/LOW RATIO ON STORAGE.
DEMAND = 0.9

months, the storage is effectively independent of severity. Above this number of low months, storage depends on both factors. The pattern of dependence depends also on the demand level in that for higher demands, the severity has less effect than it does for low demands.

7.6 COEFFICIENT OF VARIATION

To examine the effects of variance in the seasonal means, two cases of the means analysis were taken. A year with 5 low months was used and high/low ratios of 5. and 20. were studied. For each of these, CS was 0.8, correlation was 0.0 and CV for mean fractions above 0.0833 were given the values 0.3, 0.5, 0.8, 1.0, 1.5 while fractions below 0.0833 were assigned 0.5, 0.8, 1.0, 2.0, 3.0, 4.0. The results are in Figures 49 to 52 where the values shown are compared to the historically-derived values and the demand level.

Discounting the fact that the storage for the 20.0 severity level is greater than that of the 5.0 case for both demand levels, there are two patterns of storage-one for each demand level.

At $D^* = 0.0833$, the storage is increased almost equally by an increase in CV of either the wet or dry months.

At $D^* = 0.9$, the CV's of the dry months have practically no effect on the storage required. Any increase is caused by increasing the CV of the wet months.

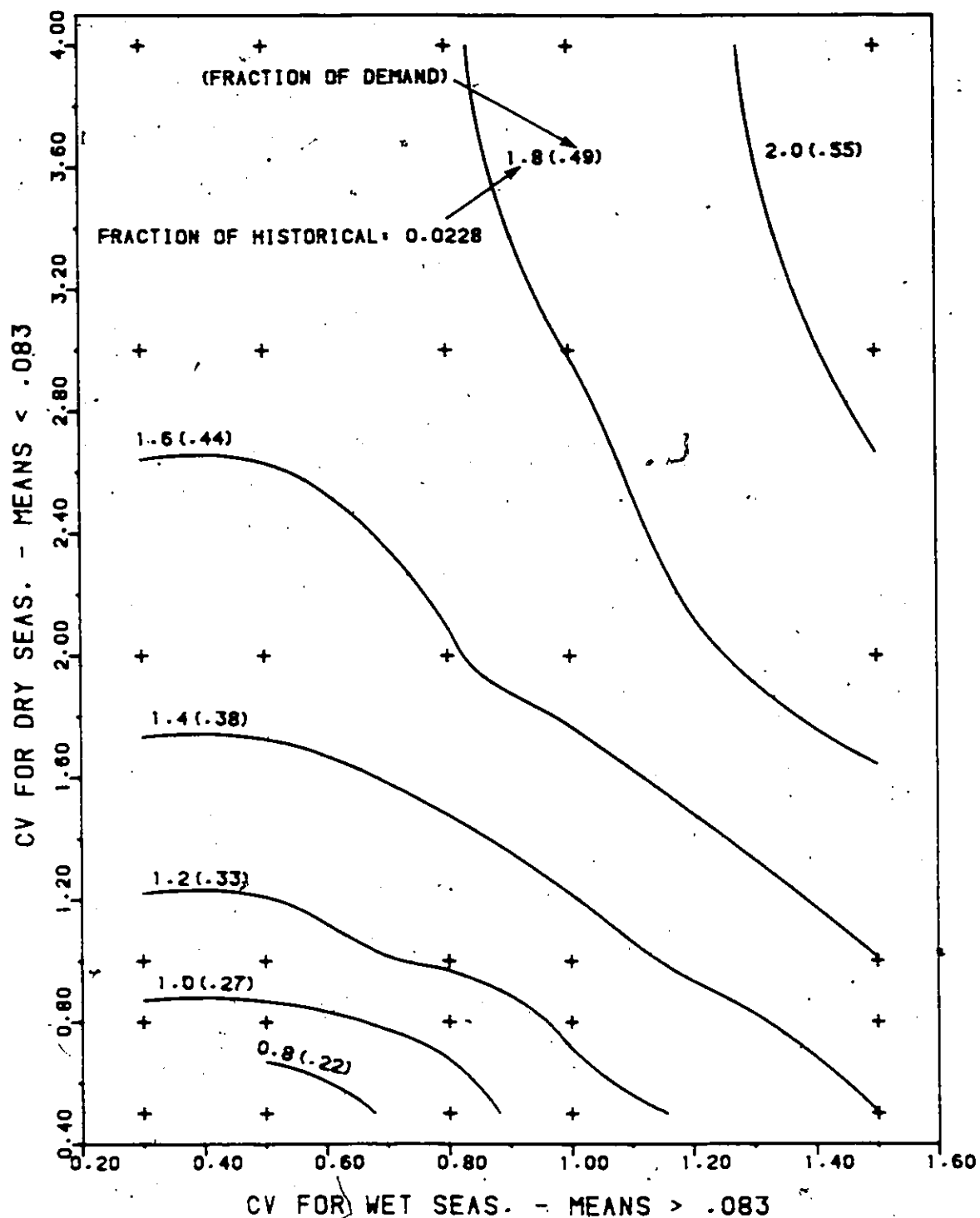


FIG. 49: EFFECT OF CV'S OF WET AND DRY SEASONS ON STORAGE.
 2 SEASONS, 5 DRY MOS., HIGH/LOW RATIO = 5.,
 CORR. = 0., CS = .8
 DEMAND = 0.0833

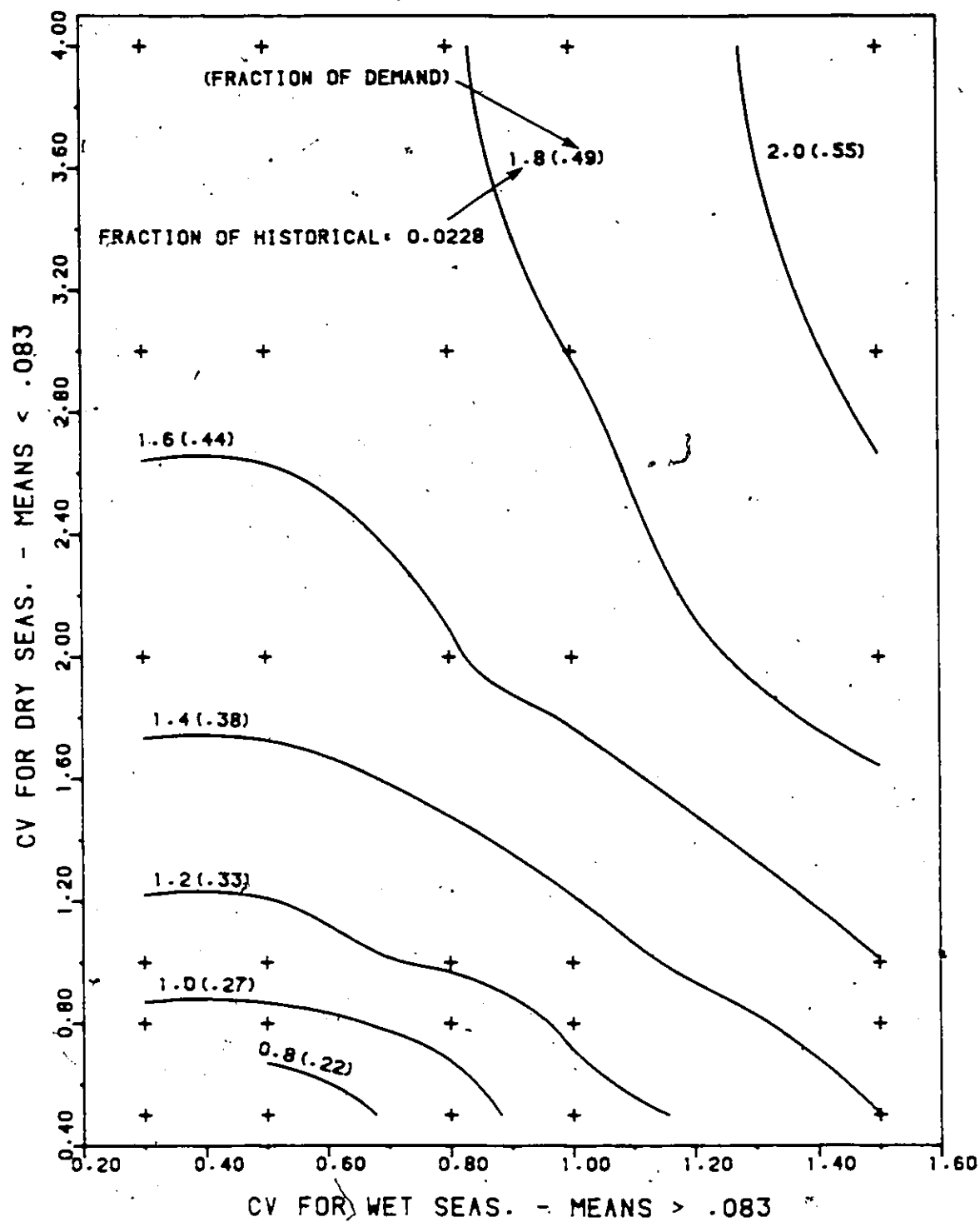


FIG. 49: EFFECT OF CV'S OF WET AND DRY SEASONS ON STORAGE.
 2 SEASONS. 5 DRY MOS.. HIGH/LOW RATIO = 5..
 CORR. = 0., CS = .8
 DEMAND = 0.0833

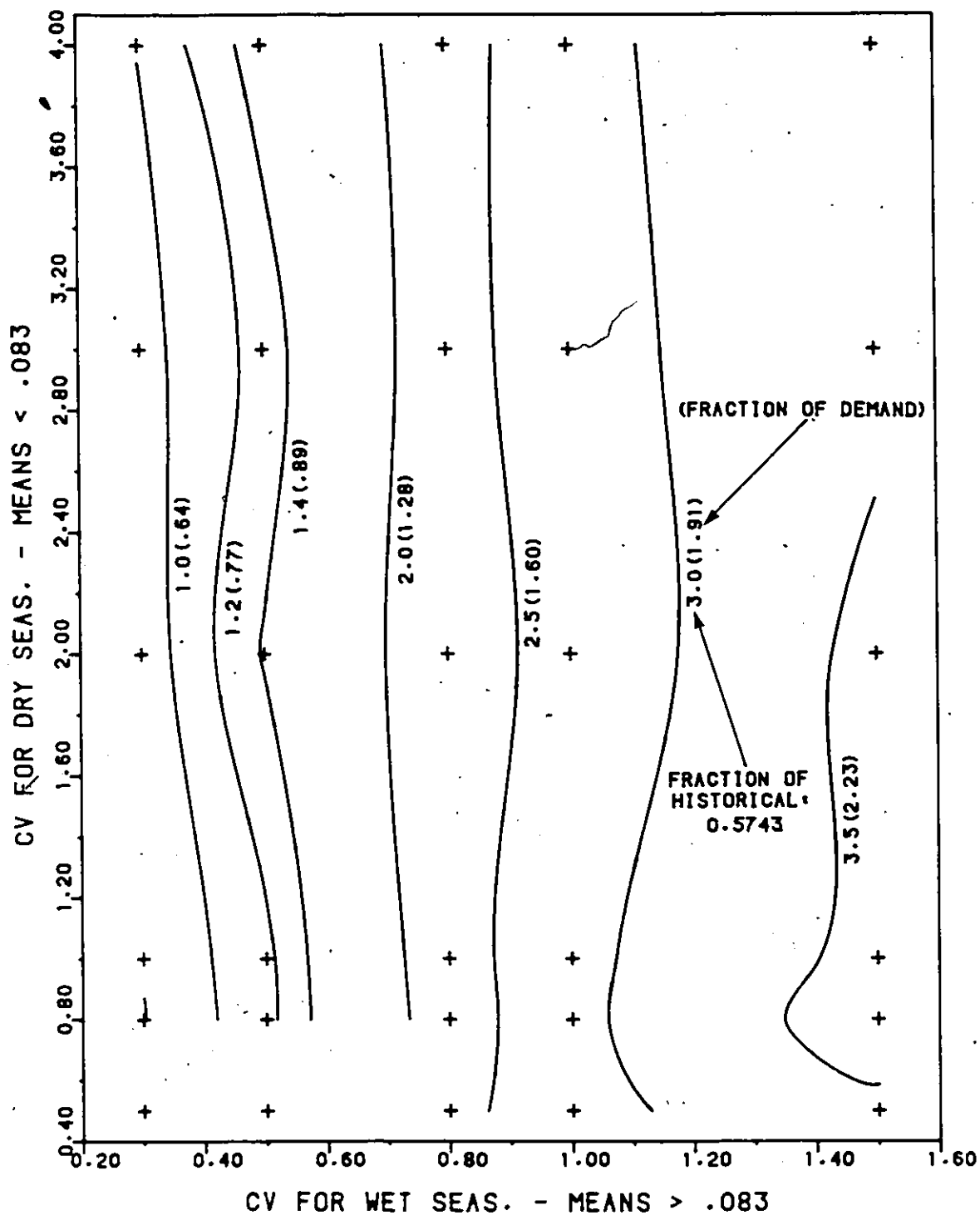


FIG. 50: EFFECT OF CV'S OF WET AND DRY SEASONS ON STORAGE.
 2 SEASONS. 5 DRY MOS.. HIGH/LOW RATIO = 5..
 CORR. = 0., CS = .8
 DEMAND = 0.9

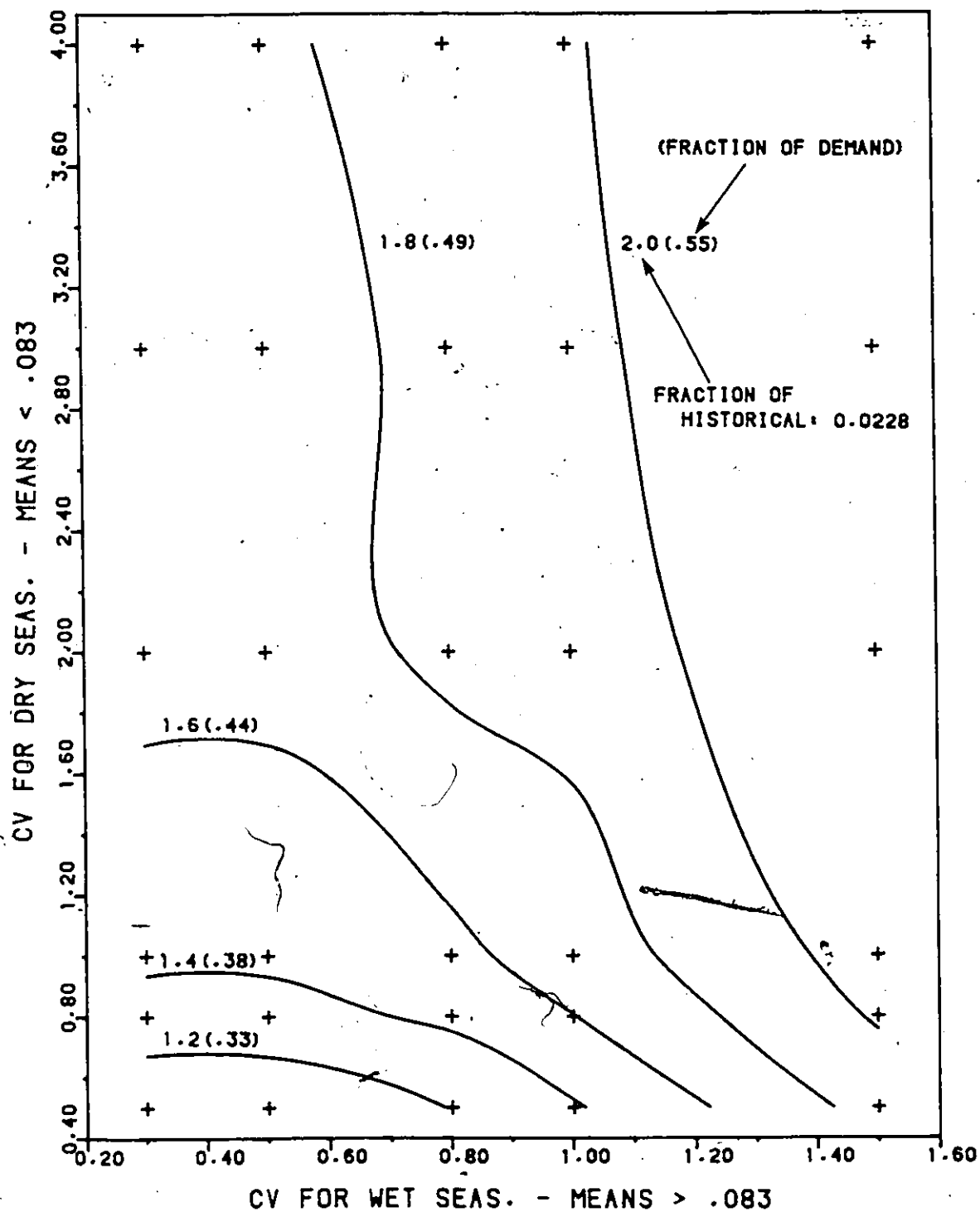


FIG. 51: EFFECT OF CV'S OF WET AND DRY SEASONS ON STORAGE.
 2 SEASONS. 5 DRY MOS.. HIGH/LOW RATIO = 20..
 CORR. = 0., CS = .8
 DEMAND = 0.0833

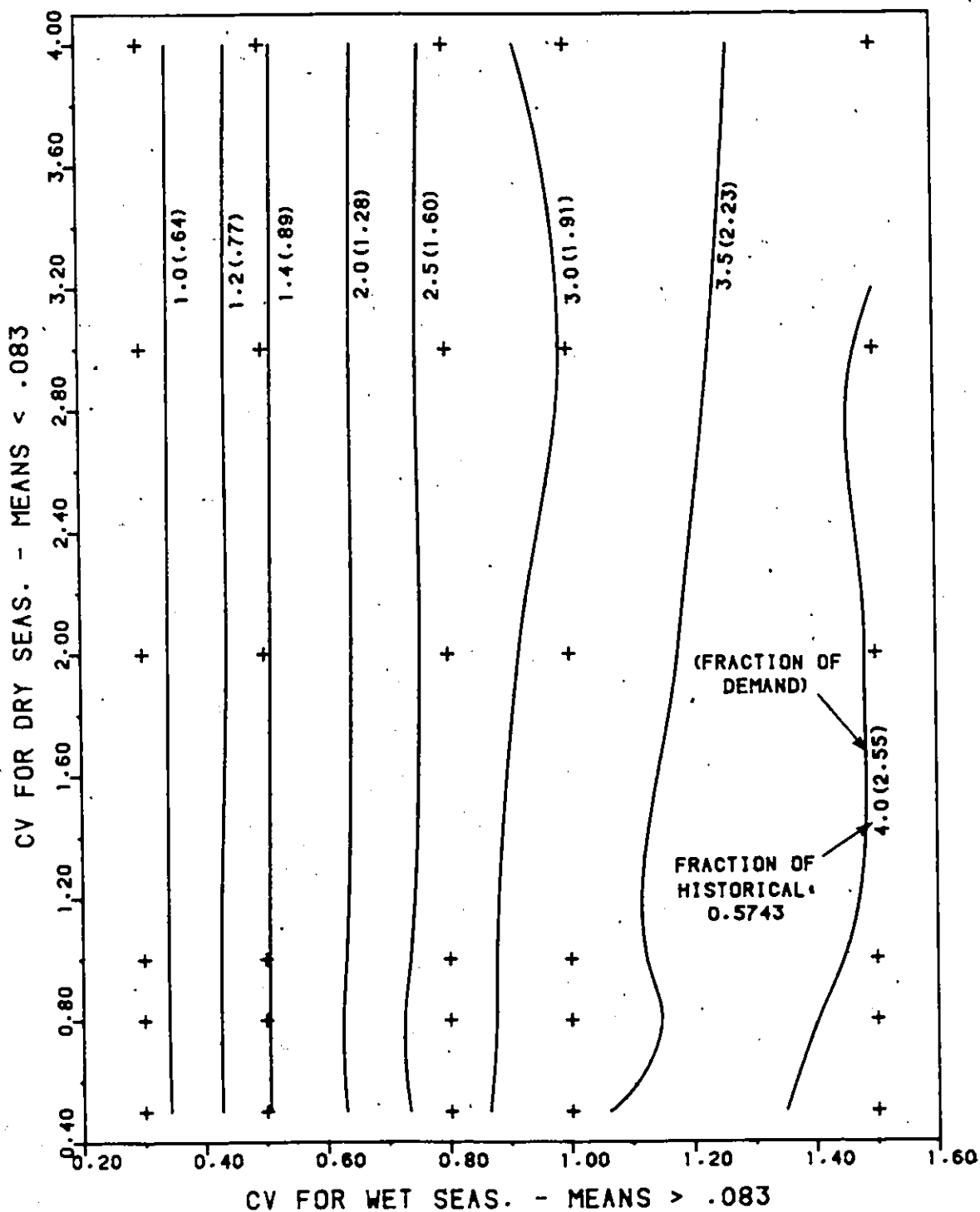


FIG. 52: EFFECT OF CV'S OF WET AND DRY SEASONS ON STORAGE.
 2 SEASONS, 5 DRY MOS., HIGH/LOW RATIO = 20..
 CORR. = 0., CS = .8
 DEMAND = 0.9

7.7 SUMMARY

Skew has a very small effect on storage. Seasonal correlation can have a considerable effect if the data exhibits high enough correlation. However, since monthly rainfall seasonal correlations are small, the effect is minimized.

The effects of drought-period parameters (length of dry period, high to low month ratio, and variation of months in wet and dry periods) are more pronounced than skew and correlation and are strongly dependent on the demand levels. Higher demands result in much greater increases in storage over the ranges of the parameters studied. However, in general, for a dry period of 4 months or less, the number of low months is the determining factor for storage as opposed to the high/low monthly ratio. Storage is determined by variances of both high and low months for low demands but for high demands, the variance of the wet months is the determining factor.

Chapter VIII
CONCLUSIONS AND DISCUSSION

8.1 SUMMARY

Rainwater, collected and stored with care, can be used as a potable water source in many areas of the world. The major cost of the system is the reservoir or tank used to hold water over from wet to dry periods.

For design purposes, the calculation of the reservoir size should involve as little data as possible and be done in a very short time. No good method exists with these characteristics, but the first step towards this is the development of a model that produces values that can be compared with simpler methods.

To this end, a search was made of reservoir-sizing models and a comparison of those that had been used previously for rainwater tanks was done. Despite difficulties in comparison due to different definitions of reliability, it was evident that one class of models, namely those involving a behaviour analysis, produced a wide range of storage values and could be altered easily to produce this range. Several behaviour analyses in the literature were unified by the introduction of a variable parameter, θ .

The computer model was developed to incorporate as many options from the literature as possible. A major addition to previous models was the development of a new algorithm for estimating a starting volume for the reservoir calculation. It was based on averaging the year-end storages calculated with the available data and an initially full reservoir.

The model was tested on rainfall data for Ottawa CDA, Canada. It was found that, while storage calculated using daily data was nearly independent of the type of behaviour analysis used, indicating that this time period led to a "true" storage value, monthly data calculations could be made to approximate the daily values by a change in the reliability of the most severe (i.e. conservative) model from 100% to 99%.

Further tests of the conservative model with simplified and standardized monthly data showed numerous features of the model. The most influential input data features were period of drought, monthly rainfall cyclicity and minimum annual rainfall.

Finally, to study the effects on storage of various patterns of easily determined rainfall parameters, a rainfall model was developed and applied a number of times and conclusions drawn.

8.2 CONCLUSIONS

When the research for this thesis began, the ultimate goal was to produce a method to calculate rainwater tank size using a minimum number of easily-derived parameters. With this method, lay designers would be able to design their systems without detailed data analysis.

This goal was not reached in its entirety. However, the tools for future investigations were developed and a reduction of the number of parameters needed was accomplished.

From the work that has been done, the following conclusions can be drawn:

1. A computerized storage model was developed. It had the following characteristics and abilities:
 - a) It simulates the operation of the reservoir using a behaviour analysis, which was found to be the most flexible method of those studied.
 - b) It has options for selection of type of behaviour analysis, reliability level, rationing and stocking.
 - c) It uses a full start, single yearly average starting value algorithm which was developed and found superior to previous methods when applied to the conservative behaviour analysis.
 - d) One type of behaviour analysis, the Yield After Spillage or Conservative analysis, will give the largest storages of the models tested.

- e) The Conservative analysis has a minimum storage equal to the demand of two data periods.

2. Performance Tests of Model

- a) When a daily calculation is done with the model, the storage calculated is nearly independent of the type of calculation and the reliability definition.
- b) If monthly data are used, it is recommended that the conservative behaviour analysis with 99% volume-based reliability be applied to approximate the daily calculation.

3. Effects of Rainfall Characteristics on Computed Storage

- a) The length of a period of no rain is a major factor in determination of storage above the minimum level.
- b) Markedly increasing storage is needed when yearly demand exceeds the minimum annual rainfall supply in the data.
- c) For demands below the minimum annual inflow, the periodic cycle of rainfall, notably monthly, accounts for much of the storage required.
- d) Monthly coefficient of skew has a small effect on storage and a single value estimated from the complete data series can be used for all seasons.

- e) Seasonal serial correlation has more effect than coefficient of skew on storage values. However, monthly rainfall has low correlation values and hence, it is not expected to be of great importance.
- f) For four or fewer dry months, storage required is nearly independent of the ratio of high to low monthly values
- g) For low demand levels, storage depends on the variation of both high and low monthly values but at high demand levels, the storage is nearly totally independent of the variation of the low months.

4. Rainfall Model Analysis

- a) The Thomas-Fiering lag-one model was found adequate to describe the rainfall for Ottawa CDA, Canada.
- b) The Like-Gamma distribution (Wilson-Hilferty Transformation) was found to reproduce the original data series parameters the best of the distributions tested when 1000 traces were generated.

e) Seasonal serial correlation has more effect than coefficient of skew on storage values. However, monthly rainfall has low correlation values and hence, it is not expected to be of great importance.

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b) The Like-Gamma distribution (Wilson-Hilferty Transformation) was found to reproduce the original data series parameters the best of the distributions tested when 1000 traces were generated.

8.3 FURTHER WORK

As always, some work has been accomplished but there are still several topics to be studied. The following is a list of a few topics that have arisen in the process of this thesis.

1. Hydrology

- A better model of the effect of snow and cold on inflow from rain is needed.
- There is a need to examine rainfall regimes to determine ranges for parameters and establish patterns.
- Further experiments could be carried out with the model developed here to determine the interrelationships among the parameters studied.

2. Storage Model

- The effect of θ on storage values should be examined.
- A field study of the demand patterns and rationing could be undertaken to develop a model for demand.
- A study of the effects of stocking could result in an economic model in order to determine a minimum cost for the combined use of rainwater and other water sources.
- The starting algorithm developed here could be tested with other data and with other behaviour analyses.

3. Synthetic Hydrology

- While all studies done here are based on Ottawa CDA data, it would be useful to study the application of

Thomas-Fiering models to other rainfall regimes,
especially those with periods with no rain.

Appendix A
PRACTICAL CONSIDERATIONS AND APPLICATION

A.1 PRACTICAL CONSIDERATIONS

A.1.1 Canadian Climate Conditions

As discussed in Section 3.2.2, snow was neglected in the data used to calculate the demand/storage/reliability curves for Ottawa CDA.

A.1.2 Variable Demand

In the model developed in this thesis, it was assumed that demand was constant. The real case is that demand depends on the amount in the storage tank. If the tank is overflowing, more water will be used and if it is low, demand will be restricted. Some attempts [55], [25] have been made to express this storage/demand relationship, but good field studies of the variation of demand have not been reported. To prepare a general demand model for use in many areas would require a number of such studies in different areas and with many socio-cultural groups. Since a demand model with field studies supporting it was not available, a neutral case (i.e. a uniform demand structure) was adopted.

A.1.3 Training in Rainwater Collection Design

At the present time (June, 1983) a series of classroom materials (slide/sound shows and training manuals) are being produced by Dr. E. Schiller and the author for the World Bank. These are intended to upgrade the hydrologic design of rainwater collectors, primarily in less developed countries.

A.2 CASE STUDY

The example given here is real. A heritage farmhouse located at Dunrobin, Ont. (close to Ottawa) required a rainwater collection system because the groundwater was unfit for human use. The details were:

Collection Area used: 135 m²

Demand: 160 l/day or 58.4 m³/year

Tank Volume: 10.7 m³

Problem: Tank runs dry every year

It was assumed that the rainfall for the farmhouse was the same as for Ottawa CDA. Figure 29 (daily line) was taken as the relevant design curve. Mean annual rainfall was 664 mm. The roof was constructed of asphalt shingle and galvanized iron. The gutters and piping were in good condition. Therefore, a runoff coefficient of 0.8 was assumed.

Effective average annual rainfall (R) = $0.8 \times 664 = 531$ mm.

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A.2.1 Case 1: analyse existing system

Step 1) Calculate Average Annual Inflow (AR)

$$\begin{aligned} \text{AR} &= \text{Area} \times \text{Effective Rainfall} \\ &= 135 \times 531/1000 \\ &= 71.7 \text{ m}^3/\text{year} \end{aligned}$$

Step 2) Calculate Demand Fraction (D/AR)

$$\begin{aligned} \text{D/AR} &= \text{yearly demand/average annual inflow} \\ &= 58.4/71.7 \\ &= 0.81 \end{aligned}$$

Note: because the demand fraction is less than 1, demand is less than supply and the system can theoretically meet the demand. If the demand fraction is greater than 1, demand will have to be decreased and/or the supply increased (by increasing the collection area) until the demand is less than the supply.

Step 3) Using Figure 29 for D/AR=0.81, it is found that S/AR is 0.34.

Step 4) Calculate Storage Volume (S)

$$\begin{aligned} S &= \text{storage fraction} \times \text{average annual inflow} \\ &= 0.34 \times 71.7 \\ &= 24.4 \text{ m}^3. \end{aligned}$$

Conclusion: the 10.7 m³ tank is too small for the combination of demand and supply of this system.

A.2.2 Case 2: increase collection area

In this situation, only half of the roof was being used. Installation of more gutters would give an area of 270 m². What storage size is needed in this case?

$$A = 270 \text{ m}^2$$

$$AR = 270 \times (664 \times 0.8)$$

$$= 143.4 \text{ m}^3$$

$$D/AR = 58.4/143.4$$

$$= 0.41$$

From Figure 29,

$$S/AR = 0.13$$

$$S = 0.13 \times 143.4$$

$$= 18.6 \text{ m}^3.$$

Conclusion: the tank is still too small.

A.2.3 Case 3: find sustainable demand

With full roof catching rain as in Case 2, what demand can be sustained by the system?

$$\text{Storage available} = 10.7 \text{ m}^3$$

As in Case 2:

$$AR = 143.4 \text{ m}^3$$

$$S/AR = 10.7/143.4$$

$$= 0.07$$

From Figure 29,

$$D/AR = 0.24$$

$$\text{Demand/year} = 0.24 \times 143.4$$

$$= 34.4 \text{ m}^3$$

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$$D/AR = 0.24$$

$$\text{Demand/year} = 0.24 \times 143.4$$

$$= 34.4 \text{ m}^3$$

Daily Demand = $34\ 400/365$

= 94 l

Conclusion: with increased area, the average demand should
be 94 l/day.

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be 94 l/day.

Appendix B

DEVELOPMENT OF A NEW STARTING STORAGE ALGORITHM

B.1 REVIEW

Usually the reliability characteristics are computed for stationary (steady state, equilibrium) conditions of reservoir operation, i.e. for operation not influenced by initial conditions of storage. (Klemes, p. 745 of [40]).

For reservoirs that are not inordinately (and uneconomically) large, which is the case being considered here, there is some point in the future at which the reservoir is expected to overflow or empty. This state will normally occur regardless of the initial storage. After the latest point for all possible starting values, the effects of the starting volume are eliminated and the reservoir is said to be in equilibrium. The true reliability can then be calculated, unbiased by the initial conditions. In a sense, it represents the long-term rather than the short-term reliability.

B.2 CONSTANT STARTING VALUES

The problem of calculating the initial storage has been solved by researchers in a number of ways. The tank is assumed full initially in the Rippl Mass Curve analysis [61] and its clone, the Thomas-Fiering Sequent Peak Method [15], by Ree et al. [59], by McMahon and Mein (p. 24+ of [47]) in their recipe for use of the behaviour analysis, and by Satijn [65]. It was assumed one-third full by Ikebuchi and Furukawa [27] although no reason was given. Perrens [52] began with a set amount, 5000 l., which could be trucked in to a rainwater system. In Schiller and Latham's work [66], the initial condition was empty or else equal to the inflow of the first rainy month.

The problem with setting initial values to a set fraction (eg. 0, 0.33, 1., etc.) of capacity is that the amount in storage varies over the year. To say in all cases that the tank should start at some particular level is unrealistic and, in most cases, false. To do this would penalize or reward the system depending on the starting date used.

B.3 TRADITIONAL CALCULATED STARTING VALUES

As outlined and illustrated by Klemes (p. 56ff of [37]), the traditional calculation is to start with a full reservoir and run the available inflow data through the algorithm to get a final value that is then used as the initial storage. This procedure is valid as long as the data used

is in full year sets (a reasonable assumption) in order to arrive at the starting volume for the proper time of the year. In an actual piece of work, Klemes et al. [40] used a slightly different approach for large reservoirs which was to start empty, let the first year's flow run in without any release and then route the inflows and withdrawals through to get an initial storage. For large structures, the storage of a full year's inflow might not lead to an overflow, but in most cases under consideration here, it would be expected to produce an initially full reservoir for step 3.

B.4 RATIONALE FOR OTHER METHODS

This having been said, it should be remembered that tank capacity at any one time of the year is not constant for all years but is a variable with an unknown probability distribution. Thus, to say that the last two initial value calculations are correct is only true in a probabilistic sense. If the rainfall patterns before the period under study were identical to the period itself, then the calculated initial storage would be correct. But, the probability of that sequence of rainfall's occurring again is nearly zero. Hence, the probability that the calculated starting volume is correct is much less than 1.

Therefore, a simple method that takes the probabilistic nature of starting value and the annual cyclicity into account would be expected to give a "better" answer.

In summary, the constraints on the choice of a starting volume are:

1. starting volume is a probabilistic variable depending on rainfall sequences.
2. the parameters of the distribution of the starting values are different for each season.
3. there is a limited amount of data available so that the same data are used to calculate the starting value and the system's demand/storage/reliability curve.
4. the present data must be used to determine a value that is the result of previous, unknown data.

The problem was examined for the conservative behaviour case.

B.5 ILLUSTRATION OF EQUILIBRIUM

First, by way of illustration of the effect of starting volume on system reliability, a calculation of the amount in store at the end of the month was made using the programme STRDEMO and forty years of rainfall data (January 1942 to December 1981) for Ottawa CDA for the case of demand = 0.5, capacity = 0.8 and initial volumes of 0., 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8. All values are fractions of mean annual inflow. The resultant values are plotted in Figure 53. All the calculations result in the same storage values after the period of adjustment shown in the figure.

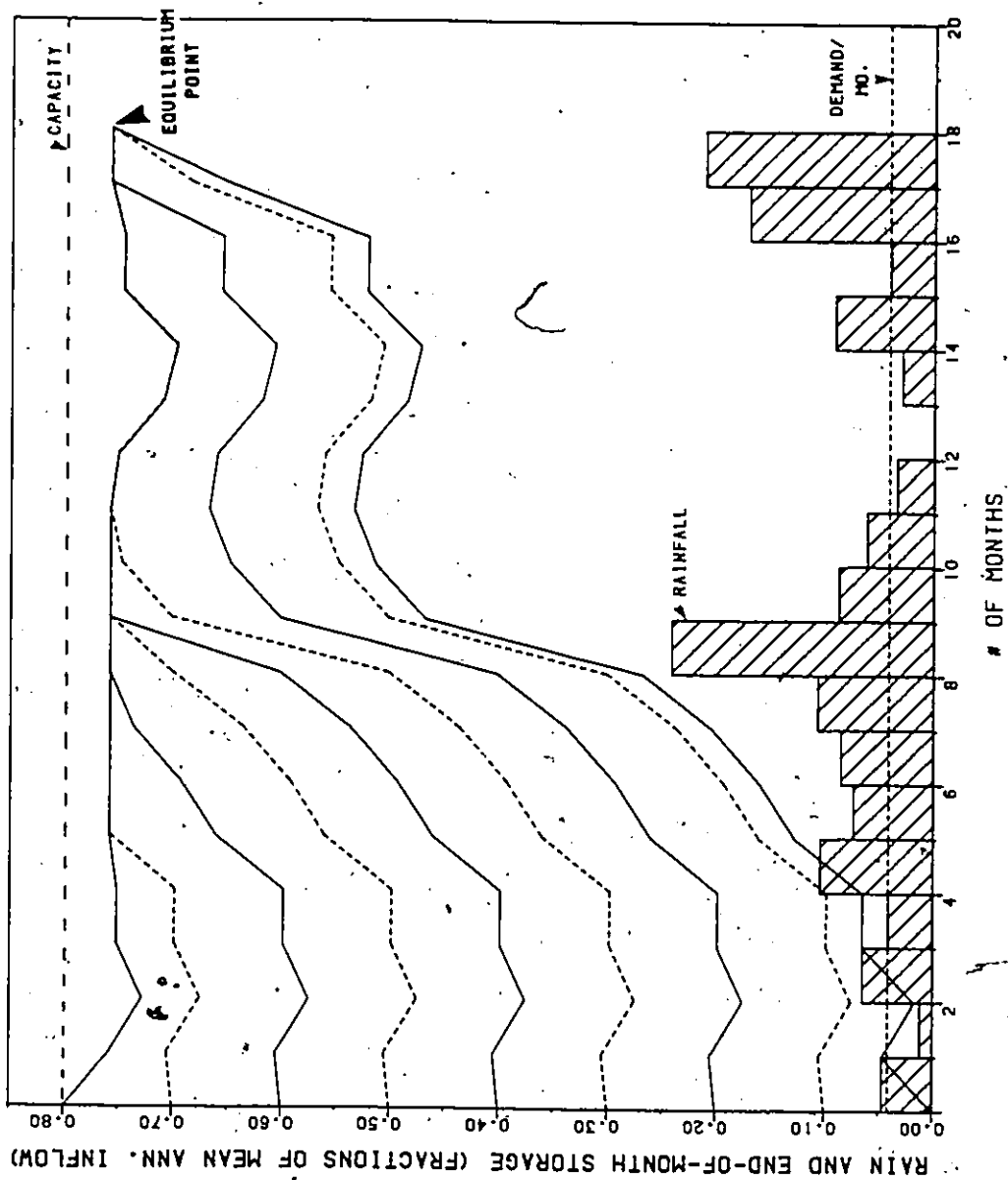


FIG. 53: EFFECT OF STARTING STORAGE. OTTAWA CDA. BEGIN. JAN. 1942
 CONS. MODEL. DEMAND = 0.5. CAPACITY = 0.8

In this case, it can be seen that equilibrium occurs when all reservoirs reach a full value but it is easy to visualize the other case where they would coincide at empty. It should be noted that the reliability is definitely affected by the starting value. For example, the calculation with 0 initially failed to meet the demand in the first month and thus was penalized because of its low starting value.

B.6 TIME TO EQUILIBRIUM

The time to equilibrium is dependent on the month of start, the level of demand and the capacity. Using data beginning January, 1942, programme STRDEMO3 was used to calculate the time to equilibrium for various combinations of demand and storage from 0.1 to 1.0 for each month. The calculation was done for starts in ten years and the minimum and maximum times to equilibrium determined. These varied from 2 months for many calculations to 228 months (19 years!) for one case of demand = 0.9, capacity = 1.0, beginning in a September. The average of times to equilibrium was calculated for each month of start and the averages over all seasons are plotted in Figure 54.

The exact reasons for the patterns lie in the particular characteristics of the rainfall series used and are of little concern for the present purpose. It is sufficient to note that the time to equilibrium

1. depends on the demand level

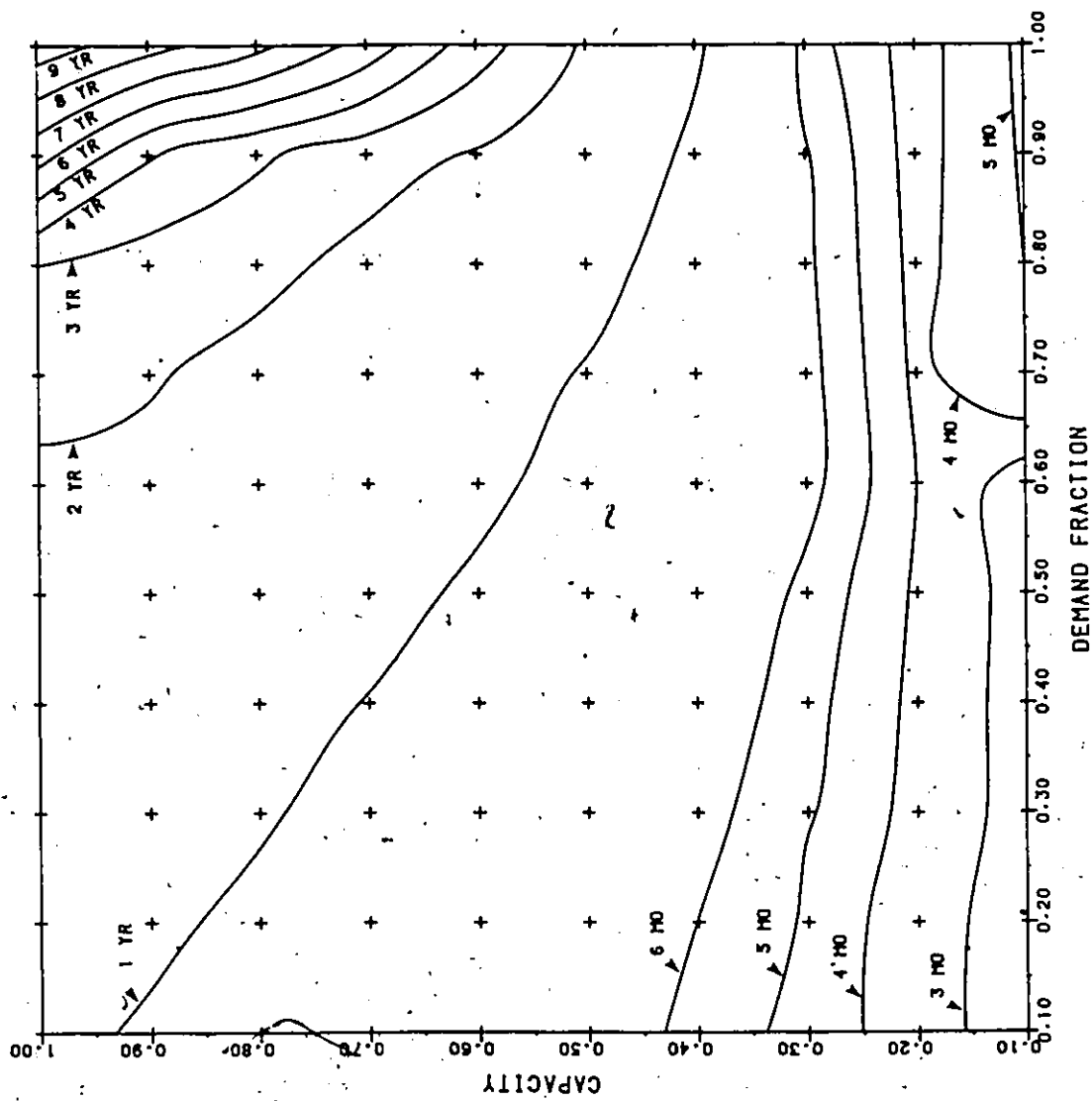


FIG. 54: AVERAGE OVER ALL SEASONS OF # OF MONTHS TO EQUILIBRIUM.
CONS. MODEL, 10-YR AVE., OTTAWA CDA, RAIN, 1942-51

2. depends on the capacity of the reservoir
3. depends to a lesser extent on the month of starting
4. is at least 20 years for inclusion of all cases met in the data tested.

B.7 COMPARISON OF METHODS OF CALCULATING STARTING VOLUME

In order to investigate possible methods of determining a correct starting volume for the conservative behaviour analysis, a certain amount of a priori knowledge was used. In computer programme STRTEST2, 40 years of data were assumed as given in a particular situation from which a starting volume would be determined by various methods. The basis of comparison was a value obtained by routing the previous 20 years of data through the algorithm. There is no ideal basis of comparison, but this one is based on a particular series that happens to be the a priori historical series of rainfall. However, it is the "correct" value if the reservoir had been operating for that period according to the procedures of the conservative behaviour calculations and, due to the 20 year length of data, would be expected to be independent of the initial starting conditions. For lack of a better standard, it is used. Both the probabilistic nature of the starting value and the effect of high or low values due to the particular month being considered were handled by taking a 60-month average of performance.

In detail, the following were done:

1. 65 years of data were read in (Ottawa CDA monthly rainfall January, 1927 to December, 1981)
2. demand and capacity levels were set
3. the first 240 months (20 years) were used to determine an a priori starting volume by direct calculation
4. the next 480 months (40 years) were used to determine a starting value for 14 different methods
5. the absolute errors between the values and the a priori value were determined
6. the first month in the 60 years of data was eliminated, a month of data added to the end and the whole process repeated
7. steps 3 to 6 were repeated 60 times (5 years) and absolute error was averaged for each method
8. steps 2 to 7 were repeated for demands and capacities of 0.1, 0.2, ..., 1.0.

The methods tested were:

1. a priori value (used for comparison), calculated by the conservative algorithm with an initially full volume,
2. Klemes et al. [40]
 - a) initially empty
 - b) the last year of a priori data is put in without demand (the effect is normally to produce an initially full value)

- c) route the 40 years through to get an initial value
- 3. Traditional Method [37]
 - a) initially full
 - b) route 40 years through
 - c) final storage is set as initial value
- 4. as for 3. but with empty start
- 5. Single average, 0 start
 - a) initially empty
 - b) route 40 years one year at a time to get 40 year-end volumes.
 - c) average them to get initial value
- 6. Single Average Full Start
 - a) as above but initially full
- 7. Double Average, 0 Start
 - a) initially empty
 - b) calculate average as above
 - c) start again with this average
 - d) repeat averaging process
- 8. Double Average, Full Start
 - a) as above but initially full
- 9. Double Average, Traditional Start
 - a) as per double averages but the initial value determined by traditional method above.
- 10. constant value = 0.
- 11. constant value = 0.2 of capacity
- 12. constant value = 0.4 of capacity

- 13. constant value = 0.6 of capacity
- 14. constant value = 0.8 of capacity
- 15. constant value = capacity

The errors of the fixed volume starts in models 10 to 15 were all higher than at least the lowest values obtained by the calculation methods, and in most cases were much higher than any of them. Constant volume starts were thus eliminated from further consideration.

A qualitative rating of the calculation methods was done. The results are in Table 9. The maximum and minimum errors were counted and recorded. There were 100 possible combinations.

TABLE 9

Rating of Initial Storage Calculation Methods

Number of Method	No. of occurrences	
	Min. Error	Max. Error
2	-	86
3	-	86
4	-	86
5	39	14
6	87	-
7	77	-
8	79	-
9	78	-

B.8 CONCLUSION

On this basis, method 6 was clearly better over a wide range of demands and capacities. It is noteworthy that the method gives better results than methods 7, 8 and 9 which involve longer calculations. In addition, the method involves approximately the same amount of computation as the traditional method.

The actual values of the average error obtained for method 6 were plotted and are presented in Figure 55. In general, demand has a greater effect on the error (higher demand = higher error) than does capacity except for high demand situations (greater than 0.8) where increasing demand produces higher error. The reasons for this pattern were not explored.

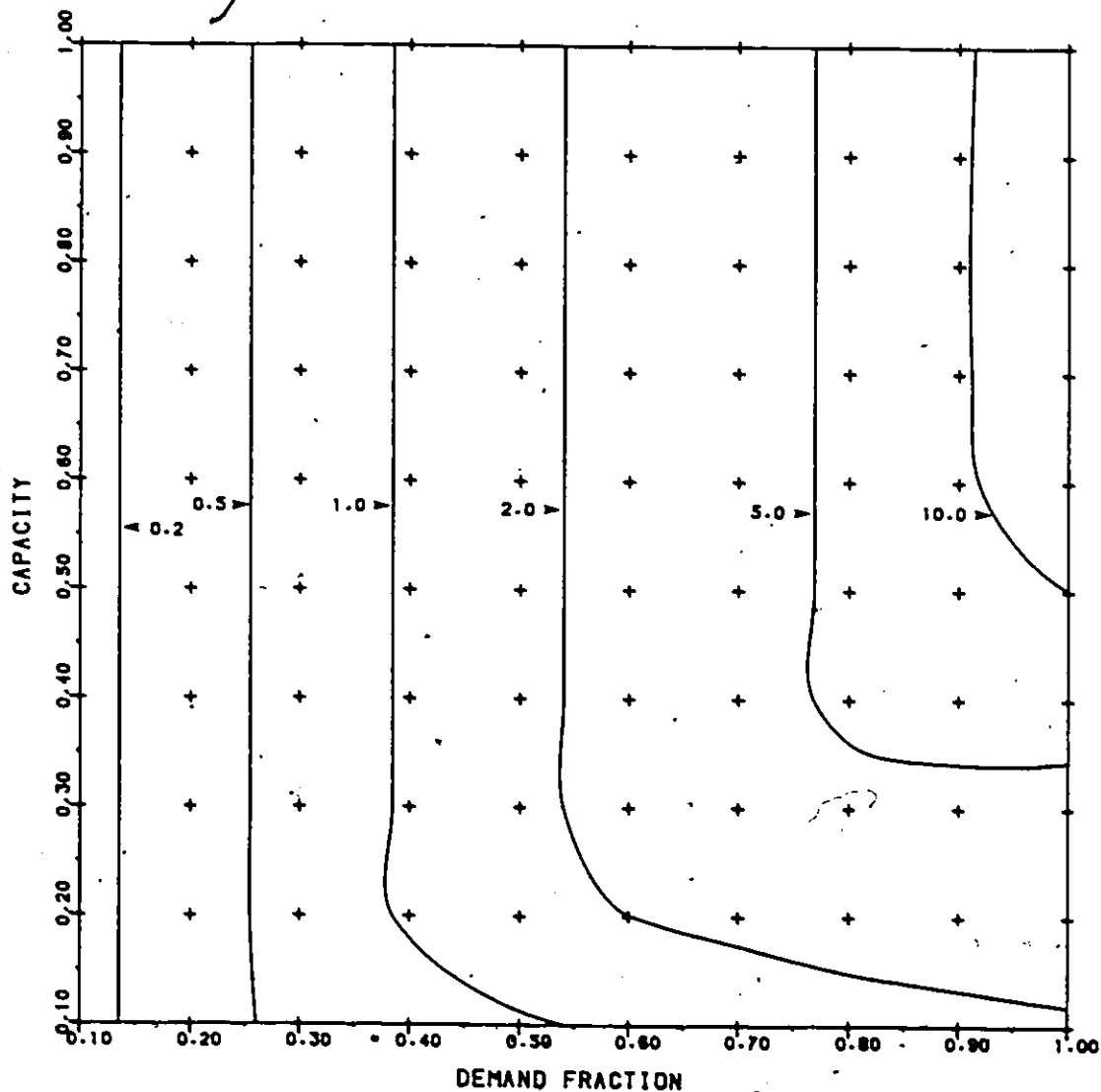


FIG. 55: TOTAL ABSOLUTE ERROR IN CALCULATION OF STARTING STORAGE
(% OF MEAN ANNUAL INFLOW).
CONS. MODEL. 5-YR AVE., OTTAWA CDA. RAIN. 1942+

Appendix C
STATISTICAL FORMULAE USED

C.1 COMMON STATISTICAL PARAMETERS

Given a data series x_i , $i = 1, \dots, N$ and letting k = the number of lags, and:

$$\Sigma = \sum_{i=1}^N$$

Then the following are the formulae for the statistics used in this thesis.

Mean:

$$u = \frac{\Sigma x_i}{N} \quad (C.1)$$

Variance:

$$\sigma^2 = \frac{\Sigma (x_i - u)^2}{(N-1)} \quad (C.2)$$

Standard Deviation:

$$\sigma = \sqrt{\sigma^2} \quad (C.3)$$

Coefficient of Variation (CV):

$$CV = \frac{\sigma}{u} \quad (C.4)$$

Correlation (see p. 53 of [22])

In general, if x_{1i} and x_{2i} , $i = 1, \dots, N$ are 2 time series with means u_1 and u_2 then the correlation between them is:

$$\rho = \frac{\sum (x_{1i} - u_1) (x_{2i} - u_2)}{\sqrt{\sum (x_{1i} - u_1)^2} \sqrt{\sum (x_{2i} - u_2)^2}} \quad (C.5)$$

Serial Correlation:

The formula for calculation is similar to Correlation but the two series are formed from a single time series by lagging one series by k lags. Thus:

$x_{1i} = x_i$ and $x_{2i} = x_{i-k}$, $i=1, \dots, N$. A cyclic nature is assumed so that if $i-k$ is 0 or negative, then $i-k = i-k+N$.

Naturally, $u_1 = u_2 = u$

Seasonal Serial Correlation:

Calculated as for correlation but N is the number of years and

x_{1i} is the set of all values in season j and

x_{2i} is the set of all values in season $j-1$. Then

$$\rho(j) = \rho$$

Partial Autocorrelation:

$$\text{Partial Auto - Correlation (PAC}_k\text{)} = \begin{cases} 1 & k = 0 \\ \rho_k & k = 1 \\ \frac{\rho_k - \sum_{i=1}^{k-1} \rho_{k-1} \phi_{k-1,i}}{1 - \sum_{i=1}^{k-1} \rho_i \phi_{k-1,i}} & k = 2, \dots \end{cases} \quad (\text{C.6})$$

where

$$\phi_{k-1,i} = \begin{cases} \text{PAC}_{k-1} & i = k-1 \\ \phi_{k-2,i} - \rho_k \phi_{k-2,k-1-i} & i = 1, \dots, k-2 \end{cases}$$

Skew (see p. 8-8 of [7]):

$$S_{\text{kew}} = \frac{N \sum (x_i - u)^3}{(N-1)(N-2)} \quad (\text{C.7})$$

Coefficient of Skew:

$$\gamma = \frac{S_{\text{kew}}}{\sigma^3} \quad (\text{C.8})$$

C.2 STEDINGER AND TAYLOR'S UNBIASED ESTIMATORS

The following are from equations 12, 13, 14 of [69]. They apply to the estimation of parameters for a number of generated traces of synthetic data series. When each trace is generated, the normal procedure is to first calculate the seasonal means and variances using the generated trace. These are then used in standard formulae to produce statistics for that trace. As pointed out in the article this results in biased estimates as the estimates do not tend to single values.

Stedinger and Taylor suggested that

1. instead of estimating the mean from each individual trace and using it in variance calculations, the mean of the historical data that is being approximated by the generated data should be used. Thus, if u_h is the historical mean:

$$\sigma_{ST}^2 = \frac{\sum (x_i - u_h)^2}{N-1} \quad (C.9)$$

$$CV_{ST} = \frac{\sigma_{ST}}{u_h} \quad (C.10)$$

2. that historical variance, σ_h^2 , be used instead of the trace variance to calculate skew and correlations. That is:

$$S_{kew} = \frac{N \sum (x_i - u)^3}{(N-1)(N-2)}$$

(C.10)

$$CS_{ST} = \frac{S_{kew_{ST}}}{\sigma_h^3}$$

(C.12)

$$\rho_k = \frac{\sum (x_i - u_h) (x_{i-k} - u_h)}{\sigma_h^2}$$

(C.13)

Appendix D

GENERATION EQUATIONS FOR SYNTHETIC DATA

The overall generation formula is due to Thomas and Fiering and is essentially as reported in Fiering and Jackson (p. 57-67 of [17], with some corrections). It is a 12-season (i.e. monthly) model with single-lag seasonal correlations.

The generalized generating equation is:

$$q_{i,j} = u_j + \rho(j) \frac{\sigma_j}{\sigma_{j-1}} \left[q_{i-1,j-1} - u_{j-1} \right] + t_1 \sigma_j \sqrt{1 - \rho^2(j)} \quad (6.2)$$

where $q_{i,j}$ is the generated value for the i th interval which is in the j th season

u_j is the mean of the values in the j th season,

σ_j is the standard deviation of the values in the j th season

$\rho(j)$ is the correlation between the values in seasons j and $j-1$.

t_1 is a random number from a desired distribution

The formulae for generating data involve generating a random variable from a normal distribution with zero mean and unit standard deviation. This was done using SSP subroutines RANDU, to generate uniformly distributed pseudo-random

values, and GAUSS, to produce normally distributed ones from them.

D.1 UNEXPONENTIATED GENERATION

D.1.1 Normal Distribution

For the normal case, u_j , $\rho(j)$, σ_j , are determined directly from the historical data series by the usual formulae (see Appendix C). Generation proceeds using the generation equation directly.

D.1.2 Like Gamma (Wilson-Hilferty)

For the like gamma case, the generation formula is used directly as in the normal case. The parameters are similar as well except for t_1 which is further transformed. This is done using the seasonal coefficient of skew, γ_j , which is estimated from the historical data series. This is corrected for serial correlation using the equation

$$\gamma_{t,j} = \frac{\gamma_j - \rho^3(j) \gamma_{j-1}}{(1 - \rho^2(j))^{1.5}} \quad (D.2)$$

(see p. 1-12 of [71] and p. 57 of [17] (corrected)). t_1 was then transformed using the Wilson-Hilferty transformation

$$t_{1,j,\gamma} = \frac{2}{\gamma_{t,j}} \left[1 + \frac{\gamma_{t,j} t_1}{6} - \frac{\gamma_{t,j}^2}{36} \right]^3 - \frac{2}{\gamma_{t,j}} \quad (D.3)$$

Negative values were set to 0.0 after the next value was generated.

D.2 EXPONENTIATED SERIES

In the lognormal case, it is assumed that the logarithms of the original series are normally distributed. However, it is not possible to simply take the logs of the data series and apply the normal case to the resultant series. In order to preserve the statistics of the original series, particularly correlation, the parameters used in the generation equation must be calculated in a special manner.

Matalas [43] presented the relationships that would preserve the original parameters for both 2 and 3 parameter cases. These were stated for a single-season, annual model. Burges (p. 199-203 of [3]) derived the equivalent equations for multiseason models. Charbeneau [5] developed an explicit solution for the annual model. The present author has not seen an explicit solution for the multiseason case and the necessary developments are given below in the next section.

For a lognormal model a distinction is made between historical data parameters ($u_x, \sigma_x, \rho_x, \gamma_x$) and those of the log series that is being generated ($u_y, \sigma_y, \rho_y, \gamma_y$). A subscript, j , on these indicates a seasonal value.

D.2.1 Log Normal 2-Parameter

For lognormal, 2 parameter

$$y_1 = \ln x_1 \quad (D.4)$$

and the u_{xj} 's, σ_{xj} 's and $\rho_x(j)$'s are determined from the data. Letting

$$\psi_j = 1 + \left[\frac{\sigma_{xj}}{u_{xj}} \right]^2 \quad (D.5)$$

then (see next section for development)

$$u_{yj} = \frac{1}{2} \ln \left[\sigma_{xj}^2 / (\psi_j^2 - \psi_j) \right] \quad (D.6)$$

$$\sigma_{yj} = \sqrt{\ln \psi_j} \quad (D.7)$$

$$\rho_y(j) = \frac{1}{\sigma_{yj-1} \sigma_{yj}} \ln \left[1 + \frac{\rho_x(j) \sigma_{xj} \sigma_{xj-1}}{u_{xj} u_{xj-1}} \right] \quad (D.8)$$

can be calculated from data values for each season and fed into the regular normal model to produce a series of q_y 's which are converted to a series of q_x 's by

$$q_x = \exp(q_y) \quad (D.9)$$

No correction for negative values is necessary.

D.2.2 Log Normal 3-Parameter

For lognormal 3 parameter

$$y_i = \ln (x_i - A_j) \quad (D.10)$$

where A_j is a seasonal location parameter. Besides the means, standard deviations and seasonal correlations for each season, a coefficient of skew γ_j is calculated from the data.

For generation, the first step is to calculate

$$\begin{aligned} \phi_j = & \left\{ \left(1 + \frac{\gamma_{xj}^2}{2} \right) + \left(\gamma_{xj}^2 + \frac{\gamma_{xj}^4}{4} \right)^{1/3} \right\}^{1/3} \\ & + \left\{ \left(1 + \frac{\gamma_{xj}^2}{2} \right) - \left(\gamma_{xj}^2 + \frac{\gamma_{xj}^4}{4} \right)^{1/3} \right\}^{1/3} - 1 \end{aligned} \quad (D.11)$$

for all j . Then the following can be calculated:

$$\sigma_{yj} = \sqrt{\ln \phi_j} \quad (D.12)$$

$$u_{yj} = \frac{1}{2} \ln \left\{ \sigma_{xj}^2 / (\phi_j^2 - \phi_j) \right\} \quad (D.13)$$

$$A_j = u_{xj} - \{ \sigma_{xj}^2 / (\phi_j - 1) \}^{1/2} \quad (D.14)$$

$$\rho_{y(j)} = \frac{1}{\sigma_{yj-1} \sigma_{yj}} \ln \left[1 + \frac{\rho_{x(j)} \sigma_{xj} \sigma_{xj-1}}{(u_{xj} - A_j)(u_{xj-1} - A_{j-1})} \right] \quad (D.15)$$

The generation then proceeds as in the normal case to produce q_y 's. These are then exponentiated by

$$q_{x,i} = \exp(q_{y,i}) + A_j \quad (D.16)$$

and negative values are set to zero.

D.3 DEVELOPMENT OF LOG NORMAL GENERATION EQUATIONS

Sources for this section:

Matalas [43]

Burges 1971 (p. 136, 199-203 of [3])

Charbeneau [5]

Fiering et al. (p. 23 of [16] (corrected))

D.3.1 2) Parameter

Matalas [43] gave the following relations that must be preserved. They are expressed in seasonal notation [3].

$$u_{xj} = \exp(u_{yj} + \frac{\sigma_{yj}^2}{2}) \quad (D.17)$$

$$\sigma_{xj}^2 = \exp(2\sigma_{yj}^2 + 2u_{yj}) - \exp(\sigma_{yj}^2 + 2u_{yj}) \quad (D.18)$$

$$\rho_x(j) = \frac{\exp(\sigma_{yj-1} \sigma_{yj} \rho_y(j)) - 1}{\{\exp(\sigma_{yj-1}^2) - 1\}^{1/2} \{\exp(\sigma_{yj}^2) - 1\}^{1/2}} \quad (D.19)$$

Similar to Charbeneau but on a seasonal basis, let

$$\psi_j = 1 + \left[\frac{\sigma_{xj}}{u_{xj}} \right]^2 \quad (D.5)$$

Substitution of (D.17) and (D.18) into (D.5) gives

$$\psi_j = \exp(\sigma_{yj}^2) \quad (D.20)$$

and thus

$$\sigma_{yj} = \sqrt{\ln \psi_j} \quad (D.7)$$

From (D.18)

$$\begin{aligned} \sigma_{xj}^2 &= \exp(2\sigma_{yj}^2) \exp(2u_{yj}) - \exp(\sigma_{yj}^2) \exp(2u_{yj}) \\ &= \exp(2u_{yj}) (\psi_j^2 - \psi_j) \end{aligned} \quad (D.21)$$

and

$$\exp(2u_{yj}) = \frac{\sigma_{xj}^2}{(\psi_j^2 - \psi_j)} \quad (D.22)$$

Hence

$$u_{yj} = \frac{1}{2} \ln \{ \sigma_{xj}^2 / (\psi_j^2 - \psi_j) \} \quad (D.6)$$

NOTE: substitution of (D.20) into (D.17) gives an alternate but equivalent equation for u_{yj} :

$$u_{yj} = \ln (u_{xj} / \psi_j^{1/2}) \quad (D.23)$$

Now, from (D.19), and substituting (D.5) and (D.20)

$$\begin{aligned} \rho_x(j) &= \frac{\exp(\sigma_{yj-1} \sigma_{yj} \rho_y(j)) - 1}{\{\psi_{j-1} - 1\}^{1/2} \{\psi_j - 1\}^{1/2}} \\ &= \frac{\exp(\sigma_{yj-1} \sigma_{yj} \rho_y(j)) - 1}{\left[\left(\frac{\sigma_{xj}}{u_{xj}} \right)^2 \right]^{1/2} \left[\left(\frac{\sigma_{xj-1}}{u_{xj-1}} \right)^2 \right]^{1/2}} \end{aligned} \quad (D.24)$$

By rearranging, taking ln's and rearranging again:

$$\rho_y(j) = \frac{1}{\sigma_{yj-1} \sigma_{yj}} \ln \left[1 + \frac{\rho_x(j) \sigma_{xj-1} \sigma_{xj}}{u_{xj} u_{xj-1}} \right] \quad (D.15)$$

D.3.2 3 parameter

Similarly, from Matalas [43] and Fiering et al. [16], the relations to be preserved are:

$$u_{xj} = A_j + \exp(u_{yj} + \frac{\sigma_{yj}^2}{2}) \quad (D.25)$$

$$\sigma_{xj}^2 = \exp(2\sigma_{yj}^2 + 2u_{yj}) - \exp(\sigma_{yj}^2 + u_{yj}) \quad (D.18)$$

$$\rho_x(j) = \frac{\exp(\sigma_{yj-1} \sigma_{yj} \rho_y(j)) - 1}{[\exp(\sigma_{yj-1}^2) - 1]^{1/2} [\exp(\sigma_{yj}^2) - 1]^{1/2}} \quad (D.19)$$

$$\gamma_{xj} = \frac{\exp(3\sigma_{yj}^2) - 3\exp(\sigma_{yj}^2) + 2}{\{\exp(\sigma_{yj}^2) - 1\}^{3/2}} \quad (D.26)$$

Similar to Charbeneau

$$\phi_j = \exp(\sigma_{yj}^2) \quad (D.27)$$

and thus

$$\sigma_{yj} = \sqrt{\ln \phi_j} \quad (D.12)$$

and solving (D.26) similar to Charbeneau's method but on a seasonal basis:

$$\begin{aligned} \phi_j = & \left\{ \left(1 + \frac{\gamma_{xj}^2}{2}\right) + \left(\gamma_{xj}^2 + \frac{\gamma_{xj}^4}{4}\right)^{1/2} \right\}^{1/3} \\ & + \left\{ \left(1 + \frac{\gamma_{xj}^2}{2}\right) - \left(\gamma_{xj}^2 + \frac{\gamma_{xj}^4}{4}\right)^{1/2} \right\}^{1/3} - 1 \end{aligned} \quad (D.11)$$

and therefore, as in the 2 parameter case, from (D.18)

$$u_{yj} = \frac{1}{2} \ln \left[\sigma_{xj}^2 / (\phi_j^2 - \phi_j) \right] \quad (D.13)$$

Further, from (D.22),

$$\begin{aligned} A_j &= u_{xj} - \exp(u_{yj} + \frac{\sigma_{yj}^2}{2}) \\ &= u_{xj} - \exp(u_{yj}) \{ \exp(\sigma_{yj}^2) \}^{\frac{1}{2}} \end{aligned} \quad (D.28)$$

Substituting using (D.12) and (D.13)

$$A_j = u_{xj} - \exp\left\{\frac{1}{2} \ln \left[\sigma_{xj}^2 / (\phi_j^2 - \phi_j) \right]\right\} \phi_j^{\frac{1}{2}} \quad (D.29)$$

and simplifying to get

$$A_j = u_{xj} - \{ \sigma_{xj}^2 / (\phi_j - 1) \}^{\frac{1}{2}} \quad (D.14)$$

From (D.19) and substituting (D.12)

$$\rho_x(j) = \frac{\exp(\sigma_{yj-1} \sigma_{yj} \rho_y(j)) - 1}{\{ \phi_{j-1} - 1 \}^{\frac{1}{2}} \{ \phi_j - 1 \}^{\frac{1}{2}}} \quad (D.30)$$

But from (D.11)

$$(\phi_j - 1)^{\frac{1}{2}} = \frac{\sigma_{xj}}{(u_{xj} - A_j)} \quad (D.31)$$

Thus

$$\rho_x(j) = \frac{\exp(\sigma_{yj-1} \sigma_{yj} \rho_y(j)) - 1}{\frac{\sigma_{xj-1}}{(u_{xj-1} - A_{j-1})} \cdot \frac{\sigma_{xj}}{(u_{xj} - A_j)}} \quad (D.32)$$

Rearranging, taking ln's and rearranging again gives:

$$\rho_y(j) = \frac{1}{\sigma_{j-1} \sigma_j} \ln \left[1 + \frac{\rho_x(j) \sigma_{xj} \sigma_{xj-1}}{(u_{xj} - A_j)(u_{xj-1} - A_{j-1})} \right] \quad (D.15)$$

Appendix E
LISTING OF COMPUTER PROGRAMMES

E.1 "NUPEARS4"

Variables in Flowchart

AVESTR - Starting storage calculated by WARMUP

D - annual demand as depth of rain

DEM - monthly demand as depth of rain

DMTOT - total depth of rain demanded

FD - demand level calculated for a given storage capacity

FDMAX, FDMIN - upper (lower) limit of FD

FD2 - FD^2

IBEGIN - number of month when calculation begins

ILEV - counts number of reliability levels

IS - counts storage levels for which demand levels will be calculated

ITOT - number of times stocking was required

KNT - flag to check if desired reliability is obtained

LR - length of rainfall series

REL - reliability measure

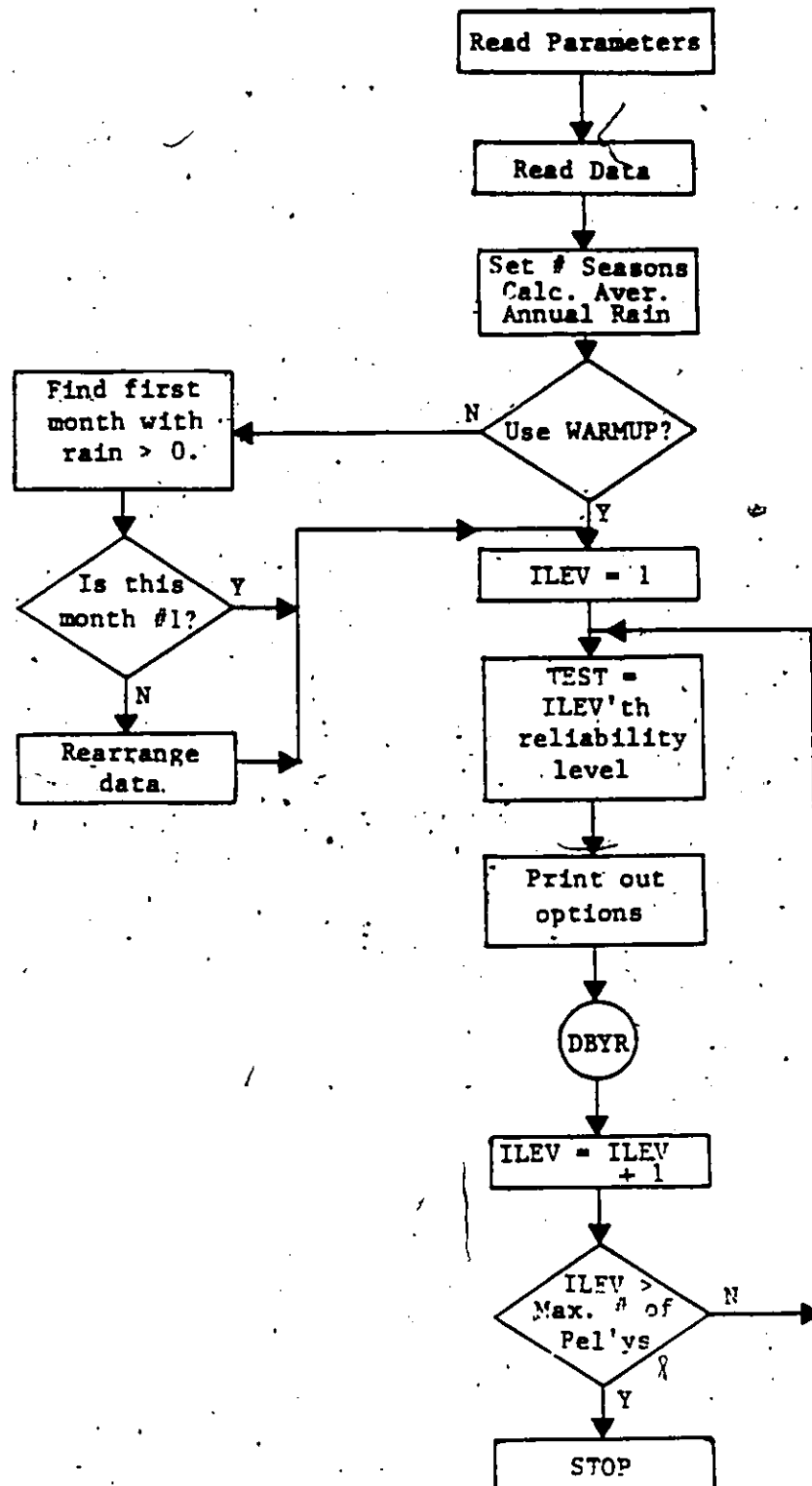
START - initial amount in storage

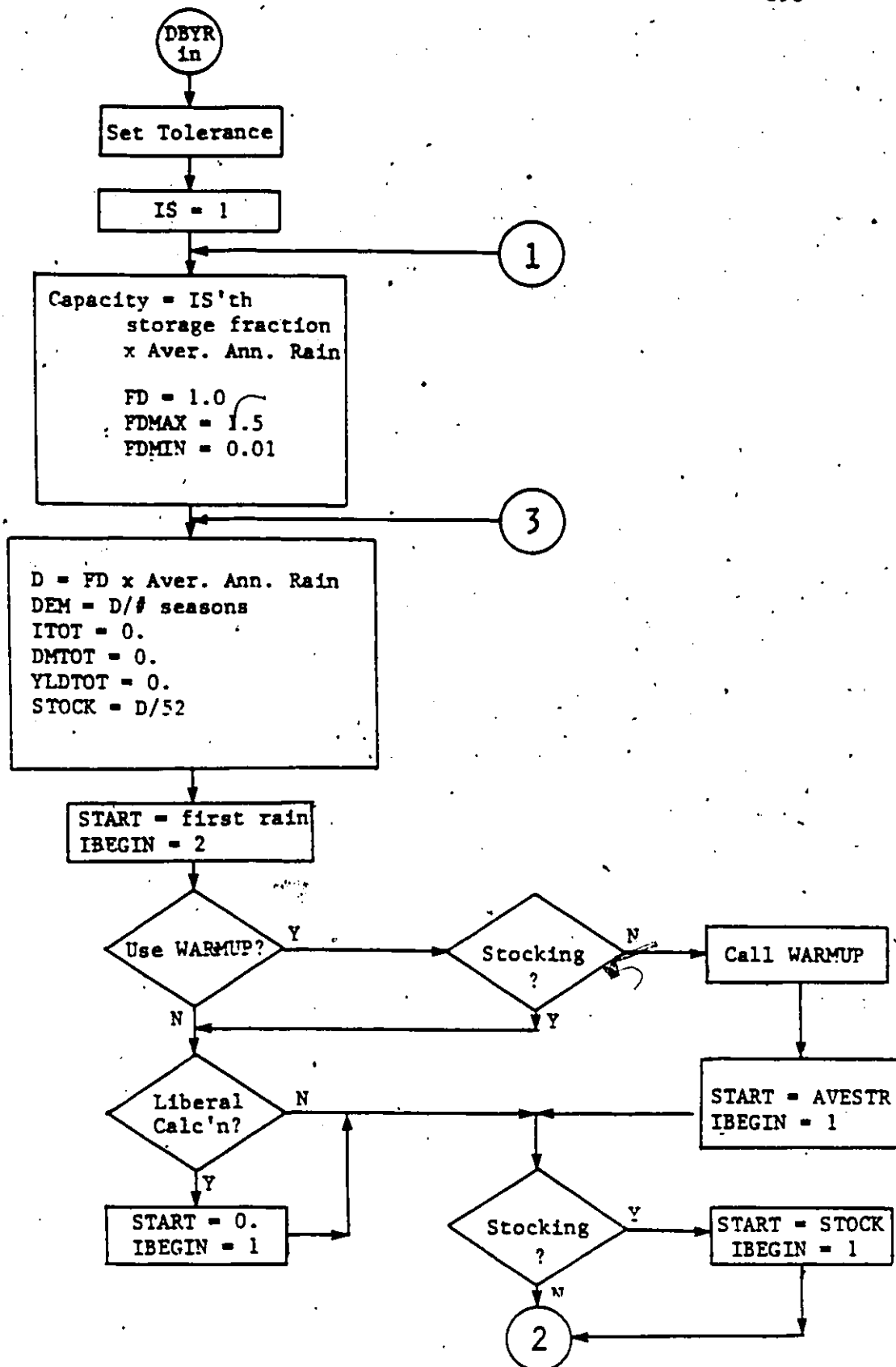
STOCK - amount of water added in case of failure

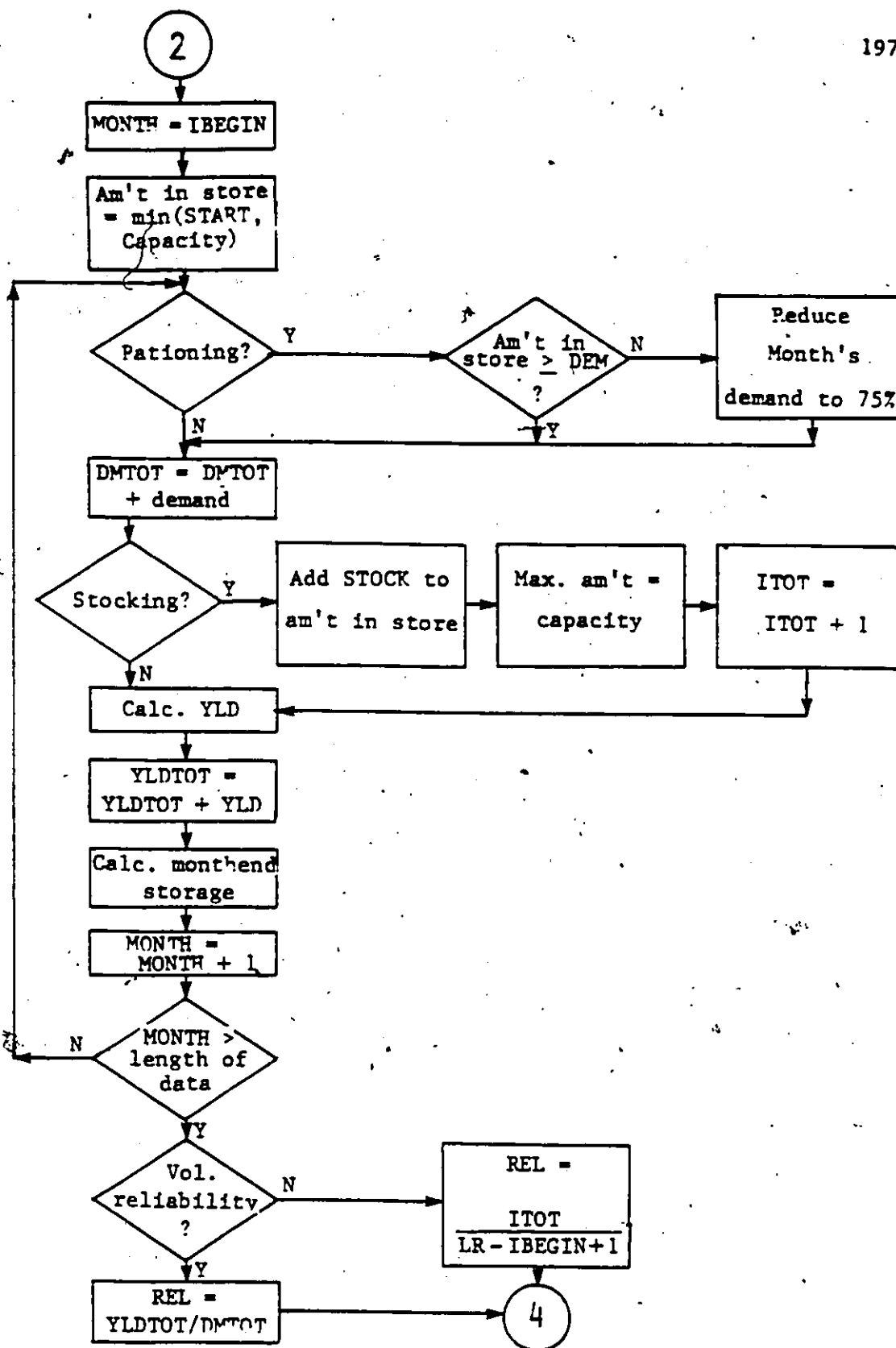
TEST - reliability of system to be obtained

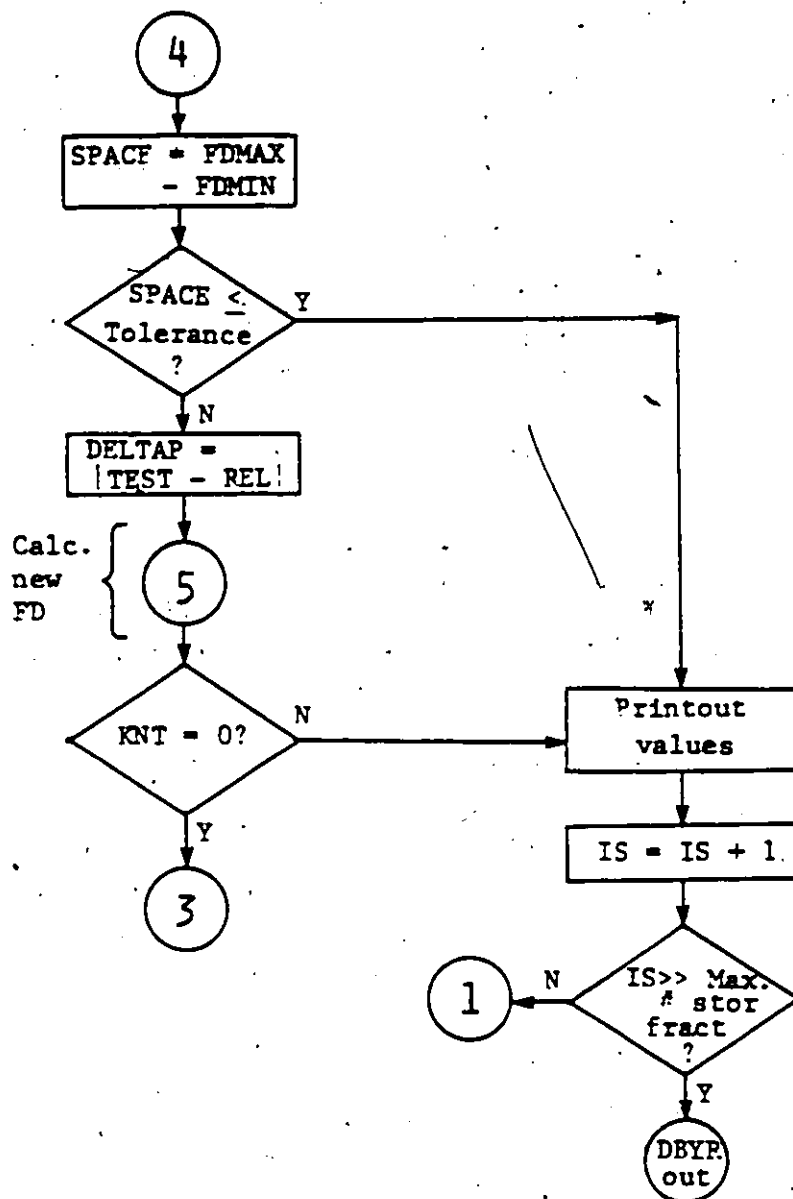
YLD - amount supplied by system in a given month

YLDTOT - total depth of rain supplied by system











5_{out}


```

C
C      #NUPEARS4
C      GIVEN RAINFALL DATA, THIS PROGRAMME CALCULATES
C      D/R RATIOS AT PRESET OR GIVEN LEVELS FOR
C      S/R RATIOS OF .01..015..025..04..06..1..15..25..4..6..10
C      VARIOUS OPTIONS ARE AVAILABLE.
C
      DIMENSION RAIN(1200),FRACS(15),AVER(100),ICNTRL(8),OUT(3,15),
7PLEVEL(8),TITLE(80)
      DATA FRACS/0.01,0.015,0.025,0.04,0.06,0.1,0.15,0.25,0.4,0.6,0.8,
11,0.3*0.0/,PLEVEL/1.,.99,.9,.8,.7,.6,.5,.4/
      LLEVEL=4
      LS=12
      READ 851,TITLE
851  FORMAT(80A1)
      READ 201,(ICNTRL(I),I=1,8)
201  FORMAT(8I2)
      IF(ICNTRL(7).EQ.0)GOTO 211
      LLEVEL=MINO(ICNTRL(7),8)
      READ 202,(PLEVEL(I),I=1,LLLEVEL)
202  FORMAT(8F7.5)
211  READ 203,LR
203  FORMAT(I7)
      READ 204,(RAIN(I),I=1,LR)
204  FORMAT(E14.7)
      IF(ICNTRL(6).EQ.0)NDIV=12
      IF(ICNTRL(6).EQ.1)NDIV=52
      IF(ICNTRL(6).EQ.2)NDIV=366
      IF(MOD(LR,NDIV).EQ.0)GOTO 205
      WRITE(6,635)NDIV
635  FORMAT('1LENGTH OF DATA NOT DIVISIBLE BY ',I5)
      STOP
205  CALL RNMEAN(LR,RAIN,AVER,AVEMIN,AVEMAX,YRRAIN,NDIV)
      IF(ICNTRL(8).EQ.1)GOTO 206
      CALL START(RAIN,IGO)
      LR2=LR-IGO+1
      IF(LR2.EQ.LR)GOTO 206
      DO 20 I=1,LR2
        RAIN(I)=RAIN(I+IGO-1)
20  CONTINUE
      IGOM1=IGO-1
      DO 21 I=1,IGOM1
        RAIN(LR2+I)=0.
21  CONTINUE
206  DO 970 ILEV=1,LLLEVEL

```

```

      TEST=PLEVEL(ILEV)
      WRITE(6,800)
800 FORMAT('1')
      WRITE(6,501)
501 FORMAT(' ',T20,'NUPEARS4',/,T22,'BY',/,T17,'BRIAN LATHAM',/,T15,
       7'CIVIL ENGINEERING',/,T17,'U. OF OTTAWA',/,T16,'OTTAWA, CANADA.')
      WRITE(6,852)TITLE
852 FORMAT('O',80A1)
      WRITE(6,633)TEST
633 FORMAT('OS/R AND D/R RATIOS FOR',F6.3,' PERFORMANCE LEVEL.')
      WRITE(6,634)
634 FORMAT(' .....')
      IF((TEST.LE.1.0).AND.(TEST.GT.0.0))GOTO 207
      WRITE(6,799)
799 FORMAT('1PERFORMANCE LEVEL IS NON-POSITIVE OR GT 1. EXECUTION TERM
       ?INATED.')
      GOTO 970
207  CONTINUE
C
C      PRINT OUT OPTIONS
C
      WRITE(6,600)
600 FORMAT('0OPTIONS IN EFFECT:')
      IF(ICNTRL(1).EQ.0)WRITE(6,601)
601 FORMAT(' NO RATIONING')
      IF(ICNTRL(1).EQ.1)WRITE(6,602)
602 FORMAT(' RATIONING')
      IF(ICNTRL(2).EQ.0)WRITE(6,603)
603 FORMAT(' CONSERVATIVE YIELD CALCULATION')
      IF(ICNTRL(2).EQ.1)WRITE(6,604)
604 FORMAT(' MEDIUM YIELD CALCULATIONS')
      IF(ICNTRL(2).EQ.2)WRITE(6,605)
605 FORMAT(' LIBERAL YIELD CALCULATIONS')
      IF(ICNTRL(3).EQ.0)WRITE(6,623)
623 FORMAT(' CONSERVATIVE STORAGE CALCULATION')
      IF(ICNTRL(3).EQ.1)WRITE(6,624)
624 FORMAT(' MEDIUM STORAGE CALCULATIONS')
      IF(ICNTRL(3).EQ.2)WRITE(6,625)
625 FORMAT(' LIBERAL STORAGE CALCULATIONS')
      IF(ICNTRL(4).EQ.0)WRITE(6,606)
606 FORMAT(' PERFORMANCE BASED ON VOLUME')
      IF(ICNTRL(4).EQ.1)WRITE(6,607)
607 FORMAT(' PERFORMANCE BASED ON TIME')
      IF(ICNTRL(5).EQ.0)WRITE(6,608)
608 FORMAT(' NO EXTERNAL STOCKING')
      IF(ICNTRL(5).EQ.1)WRITE(6,609)
609 FORMAT(' EXTERNAL STOCKING BEING DONE')
      IF(ICNTRL(6).EQ.0)WRITE(6,610)
610 FORMAT(' MONTHLY DATA')
      IF(ICNTRL(6).EQ.1)WRITE(6,611)
611 FORMAT(' WEEKLY DATA')
      IF(ICNTRL(6).EQ.2)WRITE(6,612)

```


C STRMAX - VOLUME OF STORAGE TANK PER UNIT COLLECTION AREA
 C YLD - PERIOD YIELD OF SYSTEM
 C STR - PERIOD STORAGE
 C PERF - FRACTION OF DEMAND MET BY SYSTEM
 C OUT - 3 X LFS MATRIX
 C OUT(1,I) - AN S/R FRACTION
 C OUT(2,I) - THE D/R VALUE FOR THE GIVEN PERFORMANCE
 C OUT(3,I) - THE ACTUAL PERFORMANCE VALUE USED
 C TEST - PERFORMANCE LEVEL SOUGHT
 C FD - D/R FRACTION BEING TESTED IS IN [0.01,1.0]
 C STOCK - AMOUNT ADDED FROM EXTERNAL SOURCE
 C ITOT - NUMBER OF FAILURES TO MEET DEMAND
 C DMTOT - TOTAL DEMAND MADE ON SYSTEM
 C YLDTOT - TOTAL DRAWN FROM SYSTEM (NOT INCLUDING SPILLS)
 C ICNTRL - CONTROL VECTOR
 C ICNTRL(1) RATIONING OPTION.
 C -0 - NO RATIONING
 C -1 - PERRENS-TYPE RATIONING. IF STORAGE AT
 C BEGINNING OF PERIOD IS LT. PERIOD'S DEMAND,
 C PERIOD DEMAND DECREASES TO 75% OF REGULAR
 C DEMAND.
 C ICNTRL(2) YIELD CALCULATION OPTION
 C -0 CONSERVATIVE OPTION PEARSON'S 2A
 C YIELD = MINIMUM OF:
 C A) DEMAND OR;
 C B) INITIAL STORAGE.
 C -1 MEDIUM OPTION
 C YIELD = MINIMUM OF
 C A) DEMAND OR;
 C B) INITIAL STORAGE + 1/2 PERIOD'S RAINFALL.
 C -2 LIBERAL OPTION -PEARSON'S 2B
 C YIELD = MINIMUM OF
 C A) DEMAND OR;
 C B) INITIAL STORAGE + PERIOD'S RAINFALL.
 C ICNTRL(3) STORAGE CALCULATION OPTION
 C -0 CONSERVATIVE OPTION -PEARSON'S 1A
 C STORAGE = (MINIMUM OF (TANK CAPACITY) OR
 C (INITIAL STORAGE + RAINFALL)) - YIELD
 C -1 MEDIUM OPTION
 C STORAGE = (MINIMUM OF (TANK CAPACITY) OR
 C (INITIAL STORAGE + RAINFALL - 1/2 YIELD)
 C - 1/2 YIELD
 C -2 LIBERAL OPTION -PEARSON'S 1B
 C STORAGE = MINIMUM OF (TANK CAPACITY) OR
 C (INITIAL STORAGE + RAINFALL - YIELD)
 C ICNTRL(4) TYPE OF PERFORMANCE
 C -0 (PEARSON) FRACTION OF DEMAND VOLUME MET
 C -1 FRACTION OF TIME WHEN DEMAND WAS MET
 C ICNTRL(5) STOCKING OPTION
 C -0 NO EXTERNAL SOURCE OF SUPPLY
 C PROCESS BEGINS IN SECOND PERIOD WITH FIRST
 C PERIOD'S RAINFALL IN STORE.
 C -1 EXTERNAL SUPPLY BEING USED
 C PROCESS BEGINS WITH ONE WEEK'S DEMAND IN STORE.

```

C          IF STORAGE AT BEGINNING OF ANY PERIOD IS LESS THAN
C          DEMAND, A WEEK'S SUPPLY IS ADDED TO STORAGE.
C          EVEN IF SOME OF IT IS SPILLED.
C          ICNTRL(6) TYPE OF DATA ENTERED
C              =0 MONTHLY DATA
C              =1 WEEKLY DATA
C              =2 DAILY DATA
C          ICNTRL(7) PERFORMANCE LEVEL OPTION
C              =0 AUTOMATICALLY GIVES 1.0, .99, .9, .8
C              >0 NUMBER OF PERFORMANCE LEVELS DESIRED (MAX OF 8)
C          ICNTRL(8) STARTUP OPTION
C              =0 BEGINS WITH FIRST PERIOD WITH RAIN
C              =1 BEGINS AT FIRST PERIOD BUT WITH AN INITIAL STORAGE
C                  EQUAL TO THE AVERAGE AMOUNT IN STORE AT THIS TIME OF YEAR
C                  DOES NOT WORK WITH RATIONING OPTION.
C
C          DIMENSION RAIN(1200),FRACS(15),OUT(3,15),ICNTRL(8)
C          WRITE(6,101)
101  FORMAT('O  STORAGE/      ANN.DEMAND/      FRACTION OF
          ?INITIAL STORAGE: FRACTION')
C          WRITE(6,105)
105  FORMAT(' MEAN ANN.RAIN  MEAN ANN.RAIN',T59,'(OF MEAN ANN.RAIN) (O
          ?F CAPACITY)')
C          IF(ICNTRL(4).EQ.0)WRITE(6,102)
102  FORMAT('+',T31,'DEMAND SUPPLIED (PEARSON)')
C          IF(ICNTRL(4).EQ.1)WRITE(6,103)
103  FORMAT('+',T31,'TOTAL TIME WITHOUT FAILURES')
C          IF(ICNTRL(6).EQ.0)NDIV=12
C          IF(ICNTRL(6).EQ.1)NDIV=52
C          IF(ICNTRL(6).EQ.2)NDIV=366
C          NUMYR=LR/NDIV
C          TOLER=0.0001
C          IER=0
C          DO 998 IS=1,LFS
C              STRMAX=FRACS(IS)*YRRRAIN
C
C          BEGIN ITERATIVE PROCESS
C
C          FD=1.0
C          FDMAX=1.5
C          FDMIN=0.01
C          KNT=0
C          IOP2=ICNTRL(2)/2
C          IOP3=ICNTRL(3)/2
C          OPTN2=FLOAT(ICNTRL(2))/2.
C          OPTN3=FLOAT(ICNTRL(3))/2.
224  CONTINUE
C          D=FD*YRRRAIN
C          STOCK=D/52.
C          DEM=D/NDIV
C          ITOT=0
C          OMTOT=0.
C          YLDTOT=0.

```

```

C      CALCULATION OF INITIAL STORAGE
C
C      A) DEFAULT CASE
          START=RAIN(1)
          IBEGIN=2
C      B) WARMUP OPTION
          IF(ICNTRL(8).EQ.0)GOTO 200
          IF(ICNTRL(5).EQ.1)GOTO 200
          CALL WARMUP(RAIN,DEM,NDIV,NUMYR,OPTN2,OPTN3,STRMAX,AVESTR)
          START=AVESTR
          IBEGIN=1
          GOTO 201
C      C) CASE FOR LIBERAL CALCULATION
200      IF((IOP2.NE.1).OR.(IOP3.NE.1))GOTO 201
          START=0.
          IBEGIN=1
C      D) CASE FOR STOCKING OPTION
201      IF(ICNTRL(5).NE.1)GOTO 202
          START=STOCK
          IBEGIN=1
C
202      STR=AMIN1(START,STRMAX)
          STRGO=STR
          DO 797 I=IBEGIN,LR
              DM=DEM
C
C      RATION OPTION
C
          IF((STR.GE.DEM).OR.(ICNTRL(1).NE.1))GOTO 203
          DM=DM*0.75
203      DMTOT=DM+DMTOT
          IRAT=0
          IF(ICNTRL(5).NE.1)GOTO 204
          IF(STR.GE.DEM)GOTO 204
          STR=AMIN1(STR+STOCK,STRMAX)
          ITOT=ITOT+1
          IRAT=1
204      YLD=AMIN1(DM,STR+OPTN2*RAIN(I))
          IF((YLD.GE.DM).OR.(IRAT.NE.0))GOTO 205
          ITOT=ITOT+1
205      YLDTOT=YLD+YLDTOT
          STR2=STR+RAIN(I)-OPTN3*YLD
          STR=AMIN1(STR2,STRMAX)-(1.-OPTN3)*YLD
797      CONTINUE
          IF(ICNTRL(4).NE.1)GOTO 206
          PERF=1.-FLOAT(ITOT)/FLOAT(LR-IBEGIN+1)
          GOTO 207
206      PERF=YLDTOT/DMTOT
207      IF(PERF.LE.1.0)GOTO 208
          IER=1
          WRITE(6,620)
620      FORMAT(' ERROR: A PERFORMANCE LEVEL HAS BEEN FOUND GT. 1. CHECK PE
              1RFORMANCE CALCULATION.')
          RETURN

```

```

208     IF(TEST.GE.1.0)GOTO 209
        DELTAP=ABS(TEST-PERF)
        GOTO 210
209     DELTAP=TEST-PERF
210     IF(DELTAP.GE.0.0)GOTO 211
        WRITE(6,798)
798    FORMAT('1ERROR-PERFORMANCE IS GT. 1. EXECUTION STOPPED.')
        IER=1
        RETURN
211     KNT=0
        SPACE=FDMAX-FDMIN
        IF(SPACE.GT.TOLER)GOTO 212
        KNT=1
212     IFLAG=0
        IF(KNT.NE.0)GOTO 213
        IF(TEST.NE.1.0)GOTO 214
        IF(FD.NE.FDMAX)GOTO 215
        IF(PERF.NE.1.0)GOTO 216
        KNT=1
        IFLAG=1
216     IF(PERF.GE.1.0)GOTO 215
        FD2=FDMAX*FDMIN
        KNT=0
        IFLAG=2
215     IF(FD.GE.FDMAX)GOTO 214
        IF(PERF.NE.1.0)GOTO 217
        FD2=FD*FDMAX
        KNT=0
        FDMIN=FD
        IFLAG=4
217     IF(PERF.GE.1.0)GOTO 214
        IF(DELTAP.GT.TOLER)GOTO 218
        KNT=1
        IFLAG=8
218     IF(DELTAP.LE.TOLER)GOTO 214
        FD2=FD*FDMIN
        FDMAX=FD
        KNT=0
        IFLAG=16
214     IF(TEST.GE.1.0)GOTO 219
        IF(DELTAP.GT.TOLER)GOTO 220
        KNT=1
        IFLAG=32
220     IF(DELTAP.LE.TOLER)GOTO 219
        IF(FD.NE.FDMAX)GOTO 221
        FD2=FDMAX*FDMIN
        KNT=0
        IFLAG=64
221     IF(FD.GE.FDMAX)GOTO 219
        IF(PERF.GE.TEST)GOTO 222
        FD2=FD*FDMIN-
        FDMAX=FD
        KNT=0
        IFLAG=128

```

```

222          IF(PERF.LE.TEST)GOTO 219
              FD2=FD*FDMAX
              FDMIN=FD
              KNT=0
              IFLAG=256
219          IF(IFLAG.NE.0)GOTO 223
              WRITE(6,790)
790  FORMAT('ONO DELTAP TEST DONE. CHECK PROGRAMME.')
```

IER=1
RETURN

```

223          FD=SQRT(FD2)
213          IF(KNT.EQ.0)GOTO 224
              OUT(1,IS)=FRACS(IS)
              OUT(2,IS)=FD
              OUT(3,IS)=PERF
              STORE1=STRGO/YRRAIN
              STORE2=STORE1/OUT(1,IS)
              WRITE(6,100)OUT(1,IS),OUT(2,IS),OUT(3,IS),STORE1,STORE2
100  FORMAT('O',T5,F6.4,T20,F6.4,T40,F6.4,T63,F7.5,T81,F7.5)
998  CONTINUE
              RETURN
              END
```

C
C
C

```

SUBROUTINE WARMUP (RAIN,DEM,NDIV,NUMYR,OPTN2,OPTN3,STRMAX,AVESTR)
```

C
C
C
C
C

```

    THIS SUBROUTINE CALCULATES AN INITIAL STORAGE VALUE BY
    STARTING WITH FULL STORAGE AND CALCULATING
    AN AVERAGE SEASONAL VALUE.
```

```

    DIMENSION RAIN(1200)
    STR=STRMAX
    AVESTR=0.
    DO 10 I=1,NUMYR
        DO 20 J=1,NDIV
            K=(I-1)*NDIV+J
            YLD=AMIN1(DEM,STR+OPTN2*RAIN(K))
            STR2=STR+RAIN(K)-OPTN3*YLD
            STR=AMIN1(STR2,STRMAX)-(1.-OPTN3)*YLD
```

```

20  CONTINUE
    AVESTR=AVESTR+STR
```

```

10  CONTINUE
    AVESTR=AVESTR/NUMYR
    RETURN
    END
```

C
C
C

```

SUBROUTINE START(RAIN,IGO)
```

C
C
C
C
C

```

    THIS SUBROUTINE FINDS THE FIRST MONTH OF RAINFALL THAT IS
    NON-ZERO AND RETURNS ITS NUMBER.
```


C VARIABLE LIBRARY
 C RAIN - VECTOR WITH RAINFALL DATA
 C IGO - NUMBER OF FIRST MONTH WITH NON-ZERO RAINFALL
 C

DIMENSION RAIN(1200)
 DO 975 I=1,100
 IF(RAIN(I).LE.0.0001)GOTO 975
 IGO=I
 RETURN
 975 CONTINUE
 RETURN
 END

C
 C
 C SUBROUTINE RNMEAN(LR,PRECIP,AVER,AVEMIN,AVEMAX,YRRAIN,NDIV)
 C

C THIS PROGRAMME CALCULATES ANNUAL RAINFALL, MAXIMUM AND MINIMUM
 C ANNUAL RAINFALLS, AND MEAN ANNUAL RAINFALL
 C

C NUMYR - NUMBER OF YEARS OF DATA
 C PRECIP - VECTOR WITH PERIOD RAINFALL
 C AVER - VECTOR OF LENGTH NUMYR WITH ANNUAL RAINFALLS
 C AVEMAX - MAXIMUM ANNUAL RAINFALL
 C AVEMIN - MINIMUM ANNUAL RAINFALL
 C YRRAIN - MEAN ANNUAL RAINFALL
 C NDIV - NUMBER OF PIECES OF DATA PER YEAR
 C =12 MONTHLY DATA
 C =52 WEEKLY DATA
 C =366 DAILY DATA
 C

DIMENSION PRECIP(1200),AVER(100)
 AVEMAX=0.
 AVEMIN=99999
 TOTAL=0.
 NUMYR=LR/NDIV
 DO 100 I=1,NUMYR
 SUM=0.
 DO 101 II=1,NDIV
 N=(I-1)*NDIV+II
 SUM=SUM+PRECIP(N)
 101 CONTINUE
 AVER(I)=SUM
 AVEMAX=AMAX1(AVEMAX,AVER(I))
 AVEMIN=AMIN1(AVEMIN,AVER(I))
 TOTAL=TOTAL+AVER(I)
 100 CONTINUE
 YRRAIN=TOTAL/NUMYR
 RETURN
 END

C
 C
 C

```

C      ***** DATACARD PREPARATION *****
C      FIRST CARD - TITLE (80 CHARACTERS)
C      NEXT CARD - 8 CONTROL VALUES (812)
C      1) RATIONING OPTION
C          =0 - NO RATIONING
C          =1 - RATIONING.
C      2) YIELD CALCULATION OPTION
C          =0 CONSERVATIVE OPTION
C          =1 MEDIUM OPTION
C          =2 LIBERAL OPTION
C      3) STORAGE CALCULATION OPTION
C          =0 CONSERVATIVE OPTION
C          =1 MEDIUM OPTION
C          =2 LIBERAL OPTION
C      4) TYPE OF PERFORMANCE
C          =0 FRACTION OF DEMAND VOLUME MET
C          =1 FRACTION OF TIME DEMAND WAS MET
C      5) STOCKING OPTION
C          =0 NO EXTERNAL SOURCE OF SUPPLY
C          =1 EXTERNAL SUPPLY BEING USED
C      6) TYPE OF DATA ENTERED
C          =0 MONTHLY DATA
C          =1 WEEKLY DATA
C          =2 DAILY DATA
C      7) PERFORMANCE LEVELS
C          =0 AUTOMATIC CHOICE
C          =1 NOT AUTOMATIC (PUT # OF LEVELS HERE AND LEVELS ON
C              CARD FOLLOWING CONTROLS)
C      8) STARTUP OPTION (DOES NOT CHANGE 5) )
C          =0 ITERATION BEGINS WITH FIRST PERIOD WITH RAIN
C          =1 BEGINS WITH A WARMUP STORAGE (NOT VALID FOR RATIONING)
C      NEXT CARD - PERFORMANCE LEVELS (IF ICNTRL(7) > 0) (8F7.5)
C      NEXT CARD - LENGTH OF RAINFALL (MULTIPLE OF 12.52, OR 366) (17)
C      NEXT CARDS - RAINFALL DATA (E14.7)
C      FINAL CARD IS /*
C
C
C

```

```
//GO.SYSIN DD *
```

```
TITLE GOES HERE
```

```
0 0 0 0 0 4 1
```

```
1.00000 .99000 .95000 .9
```

```
0000480
```

E.2 "CISTERN"

```

C
C      #CISTERN
C      GENERATES SYNTHETIC DATA BY FIERING MARKOV MODEL, CALCULATES
C      THE STORAGE REQUIRED OVER A RANGE FOR A GIVEN PERFORMANCE
C      LEVEL BY CONSERVATIVE (YAS) METHOD, FITS AN EV1 (GUMBEL)
C      DISTRIBUTION FOR EACH CASE, AND CALCULATES A STRAIGHT LINE
C      ON THE LOG-LOG SCALE FOR 2 CHOSEN POINTS.
C
C      DIMENSION TITLE(80),XA(12),YCS(12),ICNTRL(8),PLEVEL(8),YCV(12),
C      7YRD(12),YSD(12),RAIN(1200),FRACD(15),OUT(3,15),STOR(15,1000),
C      7STEMP(1200),XRD(12),XMN(12),XCV(12),XSD(12),XCS(12),X(15),
C      7YMEAN(12),PHI(12),NUMOK(15),A(15),U(15),ANDAT(1200),ANCV(1200),
C      7ANMN(1200)
C      DATA ICNTRL/0.0,0.0,0.0,0.0,1,1/,FRACD/.08333,.15,.3,.7,
C      7.9,10*0./
C      DOUBLE PRECISION SUM
C      PI=3.1415926
C      ISEED=94509759
C
C      ISEED SHOULD BE ODD INTEGER, 9 DIGITS OR FEWER.
C      LD=5
C      LD IS # OF NON-ZERO DEMAND FRACTIONS IN FRACD
C      IPT1=1
C      IPT2=5
C      IPT1 & IPT2 ARE THE DEMAND FRACTION CASES USED TO DRAW A STR. LINE.
C      RNEQO=0.0
C      READ(5,700)TITLE
C      700 FORMAT(80A1)
C      READ(5,701)ICHZ
C      701 FORMAT(I1)
C      ICHZ=0 -> NORMAL DISTRIBUTION
C      =1 -> LIKE-GAMMA DISTRIBUTION
C      =2 -> LOG NORMAL 2P-DISTRIBUTION
C      =3 -> LOG NORMAL 3P DISTRIBUTION
C      LLEVEL=MINO(ICNTRL(7),8)
C      READ(5,702)NUMTR
C      READ(5,702)NYR
C      READ(5,702)NSESN
C      702 FORMAT(I4)
C      READ (5,213)(PLEVEL(I),I=1,LLEVEL)
C      213 FORMAT(8F7.5)
C      READ(5,718)PROB
C      718 FORMAT(F6.4)
C      NRAIN=NYR*NSESN
C      DO 100 I=1,NSESN

```

```

      XA(I)=0.
      YCS(I)=0.
100 CONTINUE
      ICHK=ICHZ+1
C
C      READ IN PARAMETERS AND CONVERT FOR GENERATION
      GOTO(101,102,103,104).ICHK
C
C      .NORMAL CASE
101 READ(5,706)(XMN(I),XCV(I),XRD(I),I=1,NSESN)
706 FORMAT(E14.7,E15.7,E15.7)
      DO 710 I=1,NSESN
          YMEAN(I)=XMN(I)
          YSD(I)=XCV(I)-XMN(I)
          YRD(I)=XRD(I)
710 CONTINUE
      GOTO 111
C
C      GAMMA
102 READ(5,703)(XMN(I),XCV(I),XRD(I),XCS(I),I=1,NSESN)
703 FORMAT(E14.7,E15.7,E15.7,E15.7)
C
C      CORRECT HISTORICAL SKEWS FOR SERIAL CORRELATION FOR GAMMA DIST'N
      DO 707 J=1,NSESN
          JM1=J-1
          IF(JM1.EQ.0)JM1=NSESN
          RJ=XRD(J)
          RJM1=XRD(JM1)
          YCS(J)=(XCS(J)-RJM1**3*XCS(JM1))/((1.-RJ**2)**1.5)
          YMEAN(J)=XMN(J)
          YSD(J)=XCV(J)-XMN(J)
          YRD(J)=XRD(J)
707 CONTINUE
      GOTO 111
C
C      LN-2
103 READ(5,706)(XMN(I),XCV(I),XRD(I),I=1,NSESN)
      DO 708 J=1,NSESN
          XSD(J)=XMN(J)*XCV(J)
          PHI(J)=1.+(XSD(J)/XMN(J))**2
          APMI=ALOG(PHI(J))
          YSD(J)=SQRT(APMI)
          BR2=XSD(J)*XSD(J)/(PHI(J)*(PHI(J)-1.))
          YMEAN(J)=0.5*ALOG(BR2)
708 CONTINUE
      DO 709 J=1,NSESN
          JM1=J-1
          IF(JM1.EQ.0)JM1=NSESN
          AM=XRD(J)*XSD(J)*XSD(JM1)/XMN(J)/XMN(JM1)+1.
          YRD(J)=ALOG(AM)/YSD(J)/YSD(JM1)
709 CONTINUE
      GOTO 111
C

```

```

C      LN-3
104 READ(5,703)(XMN(I),XCV(I),XRO(I),XCS(I),I=1,NSESN)
      DO 712 J=1,NSESN
        XSD(J)=XMN(J)*XCV(J)
        IF(XCS(J).GT.0.)GOTO 112
        WRITE(6,113)
113 FORMAT('OTHE SKEW FOR A SEASON IS NEGATIVE. LN3 NOT SUITABLE.')
        STOP
112  XTCS2=XCS(J)*XCS(J)
      Z1=1.+XTCS2/2.
      Z2=SQRT(XTCS2+XTCS2*XTCS2/4.)
      PHI(J)=((Z1+Z2)**(1./3.))+(Z1-Z2)**(1./3.))-1.
      BR=XSD(J)*XSD(J)/(PHI(J)-1.)
      XA(J)=XMN(J)-SQRT(BR)
      APhi=ALOG(PHI(J))
      YSD(J)=SQRT(APhi)
      BR2=XSD(J)*XSD(J)/(PHI(J)*(PHI(J)-1.))
      YMEAN(J)=0.5*ALOG(BR2)
712 CONTINUE
      DO 717 J=1,NSESN
        JM1=J-1
        IF(JM1.EQ.0)JM1=NSESN
        AM=XRO(J)*XSD(J)*XSD(JM1)/(XMN(J)-XA(J))/
        ? (XMN(JM1)-XA(JM1))+1.
        YRO(J)=ALOG(AM)/YSD(J)/YSD(JM1)
717 CONTINUE
C
111 XANTOT=0.
      WRITE(6,230)
230 FORMAT('1 INPUT PARAMETERS: ',//,
      ? ' MEAN CV RO CS',/)
      DO 116 ISN=1,NSESN
        XANTOT=XANTOT+XMN(ISN)
116 CONTINUE
      IF(MOD(ICHZ,2).EQ.1)WRITE(6,232)(XMN(J),XCV(J),XRO(J),XCS(J),
      ? J=1,NSESN)
232 FORMAT(' ',E14.7,E15.7,E15.7,E15.7)
      IF(MOD(ICHZ,2).EQ.0)WRITE(6,231)(XMN(J),XCV(J),XRO(J),
      ? J=1,NSESN)
231 FORMAT(' ',E14.7,E15.7,E15.7)
C
C      BEGIN GENERATION
      ICHC=0
      IF(ICHZ.EQ.1)ICHC=1
      RAINGO=YMEAN(NSESN)
      ICNT7=ICNTRL(7)
      DO 713 ILEV=1,ICNT7
        TEST=PLEVEL(ILEV)
        DO 716 K1=1,NUMTR
          CALL TRACE(1,NYR,NSESN,YMEAN,YSD,YRO,YCS,RAINGO,ISEED,ICHC,
          ? RAIN)
          IF(ICHZ.LT.2)GOTO 25
          DO 714 I=1,NRAIN

```

```

      TEMP=RAIN(I)
      J=MOD(I,NSESN)
      IF(J.EQ.0)J=NSESN
      TEMP=EXP(TEMP)*XA(J)
      IF(TEMP.LT.RNEQO)TEMP=0.
      RAIN(I)=TEMP
714   CONTINUE
      GOTO 720
25    CONTINUE
      DO 715 IV=1,NRAIN
        IF(RAIN(IV).LT.RNEQO)RAIN(IV)=0.
715   CONTINUE
720   CONTINUE
      CALL MEAN(RAIN,NRAIN,RMEAN)
      YRRRAIN=FLOAT(NSESN)*RMEAN
      IF(ILEV.GT.1)GOTO 233
      ANMN(K1)=YRRRAIN
      DO 234 L=1,NYR
        ANDAT(L)=0.
        DO 235 L2=1,NSESN
          L3=(L-1)*NSESN+L2
          ANDAT(L)=ANDAT(L)+RAIN(L3)
235   CONTINUE
234   CONTINUE
      CALL SDEV(ANDAT,YRRRAIN,NYR,ANSDV)
      ANCV(K1)=ANSDV/YRRRAIN
233   CONTINUE
      CALL SBYR(RAIN,NRAIN,LD,FRACD.OUT,YRRRAIN,TEST,ICNTRL,IER)
      IF(IER.EQ.1)STOP
      DO 105 I=1,LD
        STOR(I,K1)=OUT(1,I)
105   CONTINUE
716   CONTINUE
      DO 106 J=1,LD
        DO 107 I=1,NUMTR
          STEMP(I)=STOR(J,I)
107   CONTINUE
          NUMOK(J)=NUMTR
          IF(NUMOK(J).GT.2)GOTO 723
          X(J)=0.0
          GOTO 106
723   NOK=NUMOK(J)
      CALL MEAN(STEMP,NOK,SMEAN)
      CALL SDEV(STEMP,SMEAN,NOK,SSD)
      CALL CSKEW(STEMP,SMEAN,SSD,NOK,SSKU)
      WRITE(6,225)J,SMEAN,SSD,SSKU
225  FORMAT('OIN DEMAND VALUE # ',I2,' STORAGE MEAN= ',E14.7,
    ?' STD. DEV.= ',E14.7,/, ' CO. OF SKEW = ',E14.7)
      CALL EV1(STEMP,NOK,SMEAN,SSD,ALPHA,UT,IERR)
      IF(IERR.EQ.0)GOTO 224
      WRITE(6,223)J,SMEAN,SSD
223  FORMAT(' IN DEMAND VALUE # ',I2,' MEAN= ',E14.7,' STD. DEV.= ',
    ?E14.7,/, ' ALPHA AND U CALCULATED BY FORMULAE')
      ALPHA=PI/SORT(6.)/SSD
      UT=SMEAN-.577215665/ALPHA
224   CONTINUE

```

```

      A(J)=ALPHA
      U(J)=UT
      Y=-ALOG(-ALOG(PROB))
      X(J)=Y/ALPHA+UT
106  CONTINUE
      CALL MEAN(ANMN,NUMTR,AMNMN)
      CALL MEAN(ANCV,NUMTR,ACVMN)
      WRITE(6,236)AMNMN, ACVMN
236  FORMAT(' - AVE ANNUAL MEAN GENERATED: ',E14.7,/, ' AVE ANNUAL CV
      ?GENERATED: ',E14.7)
C
C      PRINTOUT
      WRITE(6,800)
800  FORMAT('1')
      WRITE(6,501)
501  FORMAT(' ',T20,'CISTERN',/,T22,'BY',/,T17,'BRIAN LATHAM',/,T15,
      ?'CIVIL ENGINEERING',/,T17,'U. OF OTTAWA',/,T16,'OTTAWA, CANADA.')
      WRITE(6,852)TITLE
852  FORMAT('O',80A1)
      WRITE(6,633)TEST
633  FORMAT('OS/R AND D/R RATIOS FOR',F6.3, ' PERFORMANCE LEVEL.')
      IF(ICNTRL(4).EQ.0)WRITE(6,201)
201  FORMAT(' BASED ON FRACTION OF DEMAND VOL SUPPLIED')
      IF(ICNTRL(4).EQ.1)WRITE(6,202)
202  FORMAT(' BASED ON FRACTION OF TIME FULL DEMAND IS SUPPLIED')
      WRITE(6,203)NUMTR,NYR
203  FORMAT(' STORAGE DETERMINED BY GENERATING ',I4, ' TRACES OF DATA',
      ?I4, ' YEARS LONG DISTRIBUTED AS')
      IF(ICHZ.EQ.0)WRITE(6,204)
204  FORMAT('+',T86,'NORMAL.')
      IF(ICHZ.EQ.1)WRITE(6,205)
205  FORMAT('+',T86,'LIKE-GAMMA.')
      IF(ICHZ.EQ.2)WRITE(6,210)
210  FORMAT('+',T86,'LOGNORMAL 2 PARAMETER.')
      IF(ICHZ.EQ.3)WRITE(6,211)
211  FORMAT('+',T86,'LOGNORMAL 3 PARAMETER.')
      WRITE(6,212)PROB
212  FORMAT(' AND FITTING OF STORAGE VALUES TO EV1 DISTRIBUTION AT ',
      ?F7.4, ' LEVEL.')
      ANUM=FLOAT(NUMTR)
      ETEST=(ANUM-.25)/(ANUM+.5)
      IF(PROB.GT.ETEST)WRITE(6,222)
222  FORMAT(' RELIABILITY LEVEL OUTSIDE RANGE OF EV1 DIST',N, ' USE DISCR
      ?ETION IN INTERPRETATION.')
      WRITE(6,634)
634  FORMAT('O=====')
      IF((TEST.LE.1.0).AND.(TEST.GT.0.0))GOTO 207
      WRITE(6,799)
799  FORMAT('1PERFORMANCE LEVEL IS NON-POSITIVE OR GT 1: EXECUTION TERM
      ?INATED.')
      STOP
207  -CONTINUE
C

```

```

WRITE(6,600)
600 FORMAT('OPTIONS IN EFFECT:')
      IF(ICNTRL(1).EQ.0)WRITE(6,601)
601 FORMAT(' NO RATIONING')
      IF(ICNTRL(1).EQ.1)WRITE(6,602)
602 FORMAT(' RATIONING')
      IF(ICNTRL(2).EQ.0)WRITE(6,603)
603 FORMAT(' CONSERVATIVE YIELD CALCULATION')
      IF(ICNTRL(2).EQ.1)WRITE(6,604)
604 FORMAT(' MEDIUM YIELD CALCULATIONS')
      IF(ICNTRL(2).EQ.2)WRITE(6,605)
605 FORMAT(' LIBERAL YIELD CALCULATIONS')
      IF(ICNTRL(3).EQ.0)WRITE(6,623)
623 FORMAT(' CONSERVATIVE STORAGE CALCULATION')
      IF(ICNTRL(3).EQ.1)WRITE(6,624)
624 FORMAT(' MEDIUM STORAGE CALCULATIONS')
      IF(ICNTRL(3).EQ.2)WRITE(6,625)
625 FORMAT(' LIBERAL STORAGE CALCULATIONS')
      IF(ICNTRL(4).EQ.0)WRITE(6,606)
606 FORMAT(' PERFORMANCE BASED ON VOLUME')
      IF(ICNTRL(4).EQ.1)WRITE(6,607)
607 FORMAT(' PERFORMANCE BASED ON TIME')
      IF(ICNTRL(5).EQ.0)WRITE(6,608)
608 FORMAT(' NO EXTERNAL STOCKING')
      IF(ICNTRL(5).EQ.1)WRITE(6,609)
609 FORMAT(' EXTERNAL STOCKING BEING DONE')
      IF(ICNTRL(6).EQ.0)WRITE(6,610)
610 FORMAT(' MONTHLY DATA')
      IF(ICNTRL(6).EQ.1)WRITE(6,611)
611 FORMAT(' WEEKLY DATA')
      IF(ICNTRL(6).EQ.2)WRITE(6,612)
612 FORMAT(' DAILY DATA')
209 IF(ICNTRL(8).EQ.1)WRITE(6,614)
614 FORMAT(' WARMUP STORAGE USED TO START')
      IF(ICNTRL(7).NE.0)GOTO 208
      WRITE(6,615)
615 FORMAT(' STANDARD PERFORMANCE LEVELS')
      GOTO 209
208 WRITE(6,616)ILEV,LLEVEL
616 FORMAT(' #,I1, OF #,I1, GIVEN PERFORMANCE LEVELS')
C
      IF(ICNTRL(8).EQ.0)WRITE(6,580)IGD
580 FORMAT('OTHE PROCESS BEGINS IN MONTH # ,I3, WHEN THE RAIN BEGINS
      ?')
      IF((ICNTRL(5).NE.0).AND.(ICNTRL(8).EQ.1))WRITE(6,581)
581 FORMAT('NOTE:EXTERNAL STOCKING AND WARMUP OPTIONS CHOSEN: STOCKIN-
      ?G IS USED.')
      WRITE(6,214)
214 FORMAT('O STORAGE/ ANN.DEMAND/ # OF STORAGE VALUES
      ? IN EV1 Y=A*(X-U)')
      WRITE(6,215)
215 FORMAT(' MEAN ANN.RAIN MEAN ANN.RAIN
      ?ALPHA= U=')

```



```

      WRITE(6,634)
      DO 110 IOUT=1,LD
        WRITE(6,721)(X(IOUT),FRACD(IOUT),NUMOK(IOUT),A(IOUT),U(IOUT))
721  FORMAT('O',T5,F6.4,T20,F6.4,T37,I5,T54,E14.7,T71,E14.7)
      110 CONTINUE

```

```

C
      WRITE (6,115)XANTOT
      115 FORMAT('MEAN ANN. RAIN: ',E14.7)

```

```

C
C      CALCULATE STR. LINE ON LOG-LOG
      Y1=ALOG10(X(IPT1))
      X1=FRACD(IPT1)
      X1=ALOG10(X1)
      Y2=ALOG10(X(IPT2))
      X2=FRACD(IPT2)
      X2=ALOG10(X2)
      B=(Y1-Y2)/(X1-X2)
      A2=Y1-B*X1
      A2=10.**A2
      WRITE(6,120)FRACD(IPT1),FRACD(IPT2),A2,B
      120 FORMAT('FITTING OF FORMULA S=A*D**B USING VALUES OF D= ',F7.5,
        7' AND ',F7.5./.' A= ',E14.7.', B= ',E14.7)
      713 CONTINUE
      STOP
      END

```

```

C
C      .....
C
C      SUBROUTINE SBYR(RAIN,LR,LFD,FRACD,OUT,YRRAIN,TEST,ICNTRL,IER)
C
C      THIS PROGRAMME CALCULATES ANNUAL STORAGE/MEAN ANNUAL RAINFALL
C      RATIOS FOR A GIVEN PERFORMANCE COEFFICIENT AND DEMAND/
C      MEAN ANNUAL RAINFALL RATIOS. DEMAND AND STORAGE ARE
C      EXPRESSED AS VOLUMES PER UNIT COLLECTION AREA AND HAVE THE
C      UNITS OF DEPTH.
C
C      THIS FOLLOWS THE WORK IN "STORAGE REQUIREMENTS FOR DOMESTIC
C      RAINWATER COLLECTION SYSTEMS IN CALIF." BY PEARSON, KIM,
C      VALENTINE AND JENKINS. VARIOUS OPTIONS ARE ADDED INCLUDING
C      RATIONING (SEE PERRENS), A TIME PERFORMANCE CHARACTERISTIC,
C      CALCULATION OPTIONS, AND EXTERNAL STOCKING.

```

```

C      NOTE: LINES WITH C* WERE NOT USED IN THESIS CALCULATIONS
C

```

```

      DIMENSION RAIN(1200),FRACD(15),OUT(3,15),ICNTRL(8)
      IF(ICNTRL(6).EQ.0)NDIV=12
      IF(ICNTRL(6).EQ.1)NDIV=52
      IF(ICNTRL(6).EQ.2)NDIV=366
      NUMYR=LR/NDIV
      TOLER=0.0001
      IER=0
      DO 998 ID=1,LFD
        D=FRACD(ID)*YRRAIN

```

C BEGIN ITERATIVE PROCESS

217

C
C
C* STOCK=D/52.
DEM=D/NDIV
FS=1.0
FSMAX=1.5
FSMIN=0.005
KNT=0
IDP2=ICNTRL(2)/2
IDP3=ICNTRL(3)/2
OPTN2=FLOAT(ICNTRL(2))/2.
OPTN3=FLOAT(ICNTRL(3))/2.

224 CONTINUE

STRMAX=FS*YRRAIN
ITOT=0
DMTOT=0.
YLDTOT=0.

C
C CALCULATION OF INITIAL STORAGE

C A) DEFAULT CASE

C* START=RAIN(1)

C* IBEGIN=2

C B) WARMUP OPTION

C* IF(ICNTRL(8).EQ.0)GOTO 200

C* IF(ICNTRL(5).EQ.1)GOTO 200

CALL WARMUP(RAIN,DEM,NDIV,NUMYR,OPTN2,OPTN3,STRMAX,AVESTR)

START=AVESTR

IBEGIN=1

C* GOTO 201

C C) CASE FOR LIBERAL CALCULATION

C*200 IF((IDP2.NE.1).OR.(IDP3.NE.1))GOTO 201

C* START=0.

C* IBEGIN=1

C D) CASE FOR STOCKING OPTION

C*201 IF(ICNTRL(5).NE.1)GOTO 202

C* START=STOCK

C* IBEGIN=1

C

C*202 CONTINUE

STR=AMIN1(START,STRMAX)

C* STRGO=STR

DO 797 I=IBEGIN,LR

DM=DEM

C

C RATION OPTION

C

C* IF((STR.GE.DEM).OR.(ICNTRL(1).NE.1))GOTO 203

C* DM=DM*0.75

C*203 CONTINUE

DMTOT=DM+DMTOT

C* IRAT=0

C* IF(ICNTRL(5).NE.1)GOTO 204

C* IF(STR.GE.DEM)GOTO 204

```

      STR=AMIN1(STR+STOCK,STRMAX)
C-      ITOT=ITOT+1
C-      IRAT=1
C-204      CONTINUE
          YLD=AMIN1(DM,STR+OPTN2*RAIN(I))
C-      IF((YLD.GE.DM).OR.(IRAT.NE.O))GOTO 205
C-      ITOT=ITOT+1
C-205      CONTINUE
          YLDTOT=YLD+YLDTOT
          STR2=STR+RAIN(I)-OPTN3*YLD
          STR=AMIN1(STR2,STRMAX)-(1.-OPTN3)*YLD
797      CONTINUE
C-      IF(ICNTRL(4).NE.1)GOTO 206
C-      PERF=1.-FLOAT(ITOT)/FLOAT(LR-IBEGIN+1)
C-      GOTO 207
206      PERF=YLDTOT/DMTOT
C-207      CONTINUE
          IF(PERF.LE.1.O)GOTO 208
          IER=1
          WRITE(6,620)
620      FORMAT(' ERROR: A PERFORMANCE LEVEL HAS BEEN FOUND GT. 1. CHECK PE
          RFORMANCE CALCULATION.')
          RETURN
208      IF(TEST.GE.1.O)GOTO 209
          DELTAP=ABS(TEST-PERF)
          GOTO 210
209      DELTAP=TEST-PERF
210      IF(DELTAP.GE.O.O)GOTO 211
          WRITE(6,798)
798      FORMAT(' ERROR-PERFORMANCE IS GT. 1. EXECUTION STOPPED.')
          IER=1
          RETURN
211      KNT=0
          SPACE=FSMAX-FSMIN
          IF(SPACE.GT.TOLER)GOTO 212
          KNT=1
212      IFLAG=0
          IF(KNT.NE.O)GOTO 213
          IF(TEST.NE.1.O)GOTO 214
          IF(FS.NE.FSMIN)GOTO 215
          IF(PERF.NE.1.O)GOTO 216
          KNT=1
          IFLAG=1
216      IF(PERF.GE.1.O)GOTO 215
          FS2=FSMAX-FSMIN
          KNT=0
          IFLAG=2
215      IF(FS.LE.FSMIN)GOTO 214
          IF(PERF.NE.1.O)GOTO 217
          FS2=FS-FSMIN
          KNT=0
          FSMAX=FS
          IFLAG=4
217      IF(PERF.GE.1.O)GOTO 214

```

```

      IF(DELTA.P.GT.TOLER)GOTO 218
      KNT=1
      IFLAG=8
218      IF(DELTA.P.LE.TOLER)GOTO 214
      FS2=FS*FSMAX
      FSMIN=FS
      KNT=0
      IFLAG=16
214      IF(TEST.GE.1.0)GOTO 219
      IF(DELTA.P.GT.TOLER)GOTO 220
      KNT=1
      IFLAG=32
220      IF(DELTA.P.LE.TOLER)GOTO 219
      IF(FS.NE.FSMIN)GOTO 221
      FS2=FSMAX*FSMIN
      KNT=0
      IFLAG=64
221      IF(FS.LE.FSMIN)GOTO 219
      IF(PERF.GE.TEST)GOTO 222
      FS2=FS*FSMAX
      FSMIN=FS
      KNT=0
      IFLAG=128
222      IF(PERF.LE.TEST)GOTO 219
      FS2=FS*FSMIN
      FSMAX=FS
      KNT=0
      IFLAG=256
219      IF(IFLAG.NE.0)GOTO 223
      WRITE(6,790)
790 FORMAT('ONO DELTA TEST DONE. CHECK PROGRAMME.')
      IER=1
      RETURN
223      FS=SQRT(FS2)
213      IF(KNT.EQ.0)GOTO 224
      OUT(2,ID)=FRACD(ID)
      OUT(1,ID)=FS
      OUT(3,ID)=PERF
998 CONTINUE
      RETURN
      END

```

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.....

SUBROUTINE WARMUP (RAIN,DEM,NDIV,NUMYR,OPTN2,OPTN3,STRMAX,AVESTR)

THIS SUBROUTINE CALCULATES AN INITIAL STORAGE VALUE BY
STARTING WITH FULL STORAGE AND CALCULATING
AN AVERAGE SEASONAL VALUE.

DIMENSION RAIN(1200)
STR=STRMAX
AVESTR=0.
DO 10 I=1,NUMYR

```

      DO 20 J=1,NDIV
        K=(I-1)*NDIV+J
        YLD=AMIN1(DEM,STR+OPTN2*RAIN(K))
        STR2=STR+RAIN(K)-OPTN3*YLD
        STR=AMIN1(STR2,STRMAX)-(1.-OPTN3)*YLD
20    CONTINUE
      AVESTR=AVESTR+STR
10    CONTINUE
      AVESTR=AVESTR/NUMYR
      RETURN
      END

```

C
C
C

```

      .....

      SUBROUTINE MEAN(X,N,XMEAN)
      DIMENSION X(1200)
      DOUBLE PRECISION SUM
      SUM=0.
      DO 10 I=1,N
        SUM=SUM+X(I)
10    CONTINUE
      XMEAN=SUM/FLOAT(N)
      RETURN
      END

```

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```

      .....

      SUBROUTINE EV1(X,N,XMEAN,XSD,ALPHA,U,IER)

```

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```

      CALCULATES A MAXIMUM LIKELIHOOD FIT TO AN EXTREME VALUE
      (GUMBEL) DISTRIBUTION.
      REFERENCE: GUMBEL,E.J. - 'STATISTICS OF EXTREMES'
      P. 227 FOR INITIAL ESTIMATE OF ALPHA.
      P. 231-2 FOR B.F. KIMBALL'S ML METHOD.
      PLOTTING ON GUMBEL PAPER OF X VS. F(X)
       $F(X)=\exp(-\exp(-Y))$  WHERE  $Y=ALPHA*(X-U)$ 

```

```

      DIMENSION X(1200)
      IER=0
      TOLER=0.001
      IEND=50
      PI=3.1415926

```

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```

      INITIAL ESTIMATE OF ALPHA
      ALPHA=PI/SORT(6.)/XSD

```

```

      CALCULATE ALPHA
      IKNT=0
5    XE=0.
      E=0.
      DO 10 I=1,N
        EX=EXP(-ALPHA*X(I))
        XE=XE+X(I)*EX
        E=E+EX

```

```

10 CONTINUE
   ONE=XE/E
   ALPHA2=1./ (XMEAN-ONE)
   DELTA=ABS(ALPHA-ALPHA2)/ALPHA
   ALPHA=(ALPHA2+ALPHA)/2.
   IKNT=IKNT+1
   IF(IKNT.LT.IEND)GOTO 20
   WRITE(6,100)IEND,TOLER
100 FORMAT('OALPHA CALCULATION DOES NOT CONVERGE AFTER ',I4,' ITERATIO
   ?NS, TOLER= ',E14.7)
   IER=1
   WRITE(6,101)(X(L),L=1,N)
101 FORMAT(' ',E14.7)
   GOTO 30
20 IF(DELTA.GT.TOLER)GOTO 5
C
C   CALCULATE U
30 EU=FLQAT(N)/E
   U=ALDG(EU)/ALPHA
   CONTINUE
   RETURN
   END
C
C   .....
C
SUBROUTINE SDEV(X,XMEAN,N,SDV)
  DIMENSION X(1200)
  DOUBLE PRECISION SUM
  SUM=0.
  DO 10 I=1,N
    SUM=SUM+(X(I)-XMEAN)**2
10 CONTINUE
  VAR=SUM/FLOAT(N-1)
  SDV=SQRT(VAR)
  RETURN
  END
C
C   .....
C
SUBROUTINE TRACE(NUMTR,NYR,NSESN,YMEAN,YSD,YRO,YCS,RAINGO,ISEED,
?ICHC,RAIN)
C
C   DATA GENERATION
C
  DIMENSION OUT(12),RAIN(1200),YCS(12),YMEAN(12),YSD(12),YRO(12)
  NSTART=15
  DO 999 ITR=1,NUMTR
C   STARTING PROCEDURE
    DO 990 KGO=1,NSTART
      CALL GENER(NSESN,YMEAN,YSD,YRO,YCS,RAINGO,ICHC,ISEED,OUT)
990 CONTINUE
    DO 998 IL=1,NYR
      CALL GENER(NSESN,YMEAN,YSD,YRO,YCS,RAINGO,ICHC,ISEED,OUT)
    DO 997 I=1,NSESN

```

```

      IL2=(IL-1)*NSES+N+1
      RAIN(IL2)=OUT(I) \
997   CONTINUE
998   CONTINUE
999   CONTINUE
      RETURN
      END
C
C   .....
C
SUBROUTINE GENER(NSES,AMEAN,ASD,ACORR,ACS,RAINGO,ICHC,ISEED,RAIN)
C
C   THIS SUBROUTINE GENERATES 1 FULL YEAR OF DATA
C   NSES = # OF SEASONS
C   RAINGO IS THE STARTING VALUE FOR THE GENERATION.
C   RAINGO IS REDEFINED EACH TIME THE SUBROUTINE IS CALLED.
C   ISEED - RANDOM SEED NUMBER. SEE NOTE RE: IX IN
C   SUBROUTINE GAUSS, FOR SPECS.
C   ICHC=0 => NORMAL GENERATOR FOR NORMAL OR LN
C   =1 => GAMMA GENERATOR (HILFERTY)
C
C   DIMENSION AMEAN(12),ASD(12),RAIN(12),ACORR(12),ACS(12)
C   DO 20 J=1,NSES
C     JM1=J-1
C     IF(J.EQ.1)JM1=NSES
C   GENERATE RANDOM NORMALLY DISTRIBUTED NUMBERS
C     CALL GAUSS(ISEED,1.,0.,T)
C     IF(ICHC.EQ.0)GOTO 22
C     BRK=1.+ACS(J)*T/6.-ACS(J)**2/36.
C     T=(BRK**3-1.)**2./ACS(J)
22   C=T*ASD(J)*SQRT(1.-ACORR(J)*ACORR(J))
C     B=ACORR(J)*ASD(J)/ASD(JM1)*(RAINGO-AMEAN(JM1))
C     A=AMEAN(J)
C     RAINGO=A+B+C
C     RAIN(J)=RAINGO
20  CONTINUE
      RETURN
      END
C
C   .....
C
SUBROUTINE GAUSS(IX,S,AM,V)
C
C   - COMPUTES A NORMALLY-DISTRIBUTED RANDOM NUMBER
C   WITH S = STAND. DEV'N
C     AM = MEAN
C   - FROM SSP. LIBRARY
C   - IX IS ODD INTEGER WITH 9 OR FEWER DIGITS ON INPUT.
C   IT IS REASSIGNED A UNIFORMLY DIST'D RANDOM NUMBER
C   FOR USE IN LATER CALLS.
C
C
A=0.0
DO 50 I=1,12
  CALL RANDU(IX,IY,Y)

```

```

      IX=IY
      A=A+Y
50 CONTINUE
      V=(A-6.0)*S+AM
      RETURN
      END

```

```

C
C .....
C
C SUBROUTINE RANDU(IX,IY,YFL)
C
C - FROM SSP LIBRARY
C - COMPUTES UNIFORMLY DISTRIBUTED RANDOM REAL NUMBERS
C   BETWEEN 0 AND 1.0 AND RANDOM INTEGERS BETWEEN 0 AND
C   2**31. THE SEED IS REDEFINED ON EACH CALL.
C
C - IX - SHOULD BE SEEDED WITH AN ODD INTEGER OF 9 DIGITS OR LESS.
C   IT SHOULD BE REASSIGNED THE VALUE IY.
C - IY THE RANDOM INTEGER PRODUCED BY THE ALGORITHM.
C - YFL - UNIFORMLY DISTRIBUTED NUMBER BETWEEN 0. AND 1.0.
C - SEE SSP WRITE UP FOR REFERENCES, ETC.
C

```

```

      IY=IX*65539
      IF(IY)5,6,6
5  IY=IY+2147483647+1
6  YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END

```

```

C
C .....
C
C SUBROUTINE CSKEW(X,XMEAN,XSDV,N,XCS)
C DIMENSION X(1200)
C DOUBLE PRECISION SUM
C SUM=0.
C DO 10 I=1,N
C   SUM=SUM+((X(I)-XMEAN)/XSDV)**3
10 CONTINUE
C XCS=SUM*N/(N-1)/(N-2)
C RETURN
C END

```



```

C .....
C
C      ** DATA CARD PREPARATION **
C FIRST - TITLE
C SECOND - DISTRIBUTION CHOICE: 0-NORMAL, 1-GAMMA, 2-LN2, 3-LN3 (I1)
C THIRD - NUMBER OF TRACES TO GENERATE (I4)
C FOURTH - NUMBER OF YEARS/TRACE (I4)
C FIFTH - NUMBER OF SEASONS/YEAR (I4)
C SIXTH - PERFORMANCE RELIABILITY OF STORAGE (F7.5)
C SEVENTH - RELIABILITY LEVEL FOR EV1 DISTRIBUTION
C NEXT - SEASONAL DATA PARAMETERS (E14.7,E15.7,E15.7,E15.7)
C   FOR NORMAL - MEAN, C. OF VAR., CORRELATIONS
C   FOR GAMMA - MEAN, C. OF VAR., CORRELATIONS, C. OF SKEW
C   FOR LN2 - MEAN, C. OF VAR., CORRELATIONS
C   FOR LN3 - MEAN, C. OF VAR., CORRELATIONS, C. OF SKEW
C LAST CARD - /-

```

```

C .....
C
C //GO.SYSIN DD *
C TITLE GOES HERE

```

```

1      DISTRIBUTION
1000    # OF TRACES
0040    YEARS/TRACE
0012    SEASONS/YEAR
0.99000 STORAGE RELIABILITY
0.9150  CERTAINTY LEVEL

```

E.3 OTHER PROGRAMMES

Several other less important programmes have been used in this thesis. For the sake of space they have not been included here. Of particular note are programmes STRDEMO and STRTEST2 which have been mentioned in the text, but others have not been mentioned by name. For those interested in the details of these programmes, printouts are available from the author.

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