SYSTEMS ANALYSIS APPLIED TO RESERVOIR DESIGN IN THE JAMES RIVER BASIN

by

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I. INTRODUCTION

Since ancient times, man has been concerned with the problem of having water available when and where it is needed. When the amount needed was small, rain barrels or cisterns could often fulfill the water supply needs. However, as demand increased, it became necessary to have larger and larger storage containers. With this in mind, man soon developed the concept of placing a dam across a stream and allowing a reservoir to form behind the dam to provide the water supply. Common sense dictated that the dam be neither too large (economic cost) nor too small (insufficient supply), and methods of reservoir design became a necessity. The earliest design methods were nothing more than empirical "Rules-of-Thumb" and, although sufficient for an emerging economy, were insufficient for a more complex, industrialized society.

Systematic design methods were not really utilized until the late 1800's. The most notable and widespread of the design procedures would be that attributed to Rippl. His mass diagram, introduced in 1883, became a standard method of design for water supply reservoirs. At this time most reservoirs were designed for a single purpose, and techniques such as Rippl's were sufficiently accurate to handle the majority of problems. However, the early to mid 1900's found reservoirs being specifically designed for multipurpose operation, providing water for such items as water supply, recreation, power generation, flood control, and other purposes.

In order to handle the change from single purpose to multipurpose reservoirs, as well as meet an ever increasing demand for water, the techniques of reservoir design had to change. Rippl's procedure was no longer adequate. Other methods had to be derived, design methods which would not only handle multipurpose reservoirs, but would also be capable of designing systems where reservoirs operate together. The advent of the computer, circa 1950, allowed large scale manipulation of data, and opened the door to modern reservoir design.

Simulation models enabled the designer to evaluate many different river basin system designs. However, these models required lengthy streamflow records, usually as long as the design life of the reservoir, streamflow records which were not available in most cases. This led to the development of synthetic streamflow generators, which, when used in a simulation model, allowed a statistical evaluation of the risks and benefits inherent in each design.

As the number of designs to be evaluated was limited only by the designers imagination, search techniques were needed to help in the selection of feasible designs for evaluation. Operations research and systems analysis provided the help here, with the development of such techniques as linear programming, dynamic programming, queueing theory, and inventory theory.

The objective of this study is to investigate means of producing reservoir system designs capable of meeting future demands at a minimum initial cost. To do this, a stochastic linear programming model for optimizing the storage capacity and operations of a single reservoir is extended to a system of reservoirs operating together. Resulting system designs are then evaluated by a simulation model using synthetically generated streamflow.

II. LITERATURE REVIEW

The classical method of storage determination is the mass diagram developed by Rippl in 1883. This method examines the historical record to determine differences between surpluses and shortages from mean flow. The difference between the maximum surplus and maximum shortage, known as the range, is used as the basis of the storage estimate. (42) Obvious shortcomings of this method are that it uses only the historic record which, in all likelihood, will never occur again, and it provides no means of establishing the risk of reservoir failure in periods of low flow. Fiering points out that this technique is sensitive to the operating rule in use for the reservoir. (9)

Most planners using mass curve analysis have assumed the so-called "normal" operating policy of releasing only the demand, or spilling water when the reservoir contents plus inflow are greater than capacity. This is in spite of the possibility of unnecessary economic losses due to spillage or waste. Fiering (9) describes a mass diagram technique developed by Harold A. Thomas, Jr. for determining an optimal storage and release schedule, where the draft can vary cyclically and always be met, with the reservoir contents going to zero at least once in the interval considered. This technique, the "Sequent Peak" method, may also be used to define a "storage yield" function to determine storages needed to meet various desired drafts.

Langbein (23) used queueing theory to calculate required storages to meet target drafts, given normally distributed inflows to the reservoir. A significant conclusion from his work is that as the target draft approaches the mean annual flow or as the desired draft becomes more uniform (i.e., its variance approaches zero), the required storage grows without bound.

The development of operations research techniques during World War II, and the introduction of the digital computer shortly thereafter, has had a profound effect upon water resources systems design. The computer could be programmed to do not only the tedious bookkeeping of a reservoir routing problem, but also to use operating rules more flexible and, consequently, more complex than the "normal" procedure used previously.

One of the first river basin simulations was of the Nile River in 1955 by Morrice and Alan. (17) The objective of this simulation was to find the combination of procedures and structures which would maximize available irrigation water.

The Harvard Water Program's book, Design of Water Resources Systems, published in 1962, represented one of the earliest attempts to use simulation and optimization techniques in the economic design of entire water resources systems. This program provided a major impetus to the current interest in the development of synthetic streamflow generators.

Significant works in the simulation field since the Harvard group's initial publication include Hufschmidt and Fiering's Simulation Techniques for Design of Water Resource Systems, 1966, (18) which describes the Lehigh and Delaware River simulation projects, and Robert K. Davis's study of the Potomac River in 1967, The Range of Choice in Water Management. (5)

Various optimization techniques have been used in the search for optimal water resources designs. Dynamic programming was first applied to the problem of hydroelectric power generation by J. D. C. Little in 1955. (6) Warren Hall and several collaborators have also done extensive research into the use of dynamic programming in water resources operations and design, particularly in the planning of the California aqueduct system. (14) In a series of related papers involving dynamic programming, G. K. Young (50) developed techniques for determining reservoir operating rules, W. N. Fitch (11,12) optimized the operation of a multi-purpose water resource system, and J. M. Morgan (33) investigated the sensitivity of Fitch's results to various recreation policies.

Whereas many water resources studies have been done using dynamic programming, linear programming has also been used extensively. Many of the linear programming studies have been of steady state matters, such as maintainance of water quality standards. C. Revelle, D. P. Loucks, and W. R. Lynn, among others, have published many papers on the use of linear programming in water resources design. J. S. Bargur, H. C. Davis, and E. M. Lofting (1) made an extensive study of wastewater management in the San Francisco Bay area, utilizing linear programming to find an optimal waste discharge pattern, and then using this pattern as a constraint in another linear program to find optimal treatment levels.

D. P. Loucks and M. Gablinger (13) optimized reservoir operations by both linear and dynamic programming, obtaining the same results in each case. They pointed out that the dynamic programming solutions to their problems took far less time to solve than the linear programming solutions and were not as subject to the round-off error in the computer as the linear programming solution. On the other hand, the dynamic programming solution required a unique computer program, while the linear program could be solved by a pre-coded program.

C. Revelle, E. Joeres, and W. Kirby (39,40) presented a stochastic, or "chance constrained", linear programming model for reservoir design and operations based upon a linear decision rule for determining monthly releases. It provided a straightforward method of finding optimal storages and operating rules for multipurpose reservoirs. D. P. Loucks (24) and E. M. Eisel (7) criticized this approach, suggesting instead that the availability of more sophisticated models precludes the need for simpler models like the linear decision rule.

Joeres (21) applied the linear decision rule model to the operation of the raw water resources of the Baltimore, Maryland, water supply. The operating rules obtained from the linear decision rule were evaluated by a simulation program which calculated operating costs of existing and proposed operating rules. The results shown indicate that significant savings are possible by the use of the linear decision rule model.

Streamflow Synthesis

One of the earliest methods of synthesis was proposed by Hazen (16) in 1914. He combined annual mean flows of several streams into a single sequence which was used in conjunction with other flow statistics and the desired level of stream regulation to arrive at a flow sequence useable for a first approximation to a reservoir design storage capacity.

Sudler (43) proposed a deck of fifty cards, each with a "representative" annual flow printed on it. By shuffling and dealing the deck, flow sequences of any desired length could be created. Although each sequence would have the same average and standard deviation as the historic flows, the correlation between flows in successive years would, in all likelihood, bear little resemblance to that observed in the historic flows.

In the Harvard Water Program's book, The Design of Water Resource Systems, H. A. Thomas, Jr. and M. B. Fiering (44) presented a method of generating serially correlated monthly flows. Theirs was a regression model with each month's flow being a function only of the previous month's flow plus a random term. Because these flows have a property of markov chains, (i.e., they depend only on the flow or state that precedes it in time), the generator is called "markovian." Examination of the generated streamflows for the study described in the book showed that making the generated flows depend on more than the previous month's flow did not significantly improve results.

In the original Thomas-Fiering generator, the random term, and hence the generated flows, were normally distributed. This meant that most of the flows were not less than the average flow as in nature, (i.e., the flows were not positively skewed), and that negative flow values could be and were generated. When negative flows were generated, they were either set to zero or assigned some small positive value. Use of the log-normal distribution for the flows (i.e., generating logarithms of flows then exponentiating to get flows) guarantees that no negative flows are generated, for logarithms are undefined for flows less than zero. Synthetic flows with the skewness of the historic flows are also generated with the log-normal distribution. Other means of generating skewed flows include the use of gamma distributions for the random term, or approximations to gamma distributions.

One of the most commonly used approximations to a gamma distribution for streamflow generation is the "Wilson-Hilferty" transformation described by Fiering. (9) It is used to transform normally distributed number to a distribution approximating a gamma distribution. T. A. McMahon and A. J. Miller (31) found that this approximation failed to reproduce observed skewnesses greater than three or four, depending upon the serial correlation present between flows in successive months. To circumvent this effect, they suggested taking logarithms of the flows as an initial skewness reduction measure, followed by the use of the Wilson-Hilferty transformation to generate logarithms. William Kirby (22) has suggested a modification of the Wilson-Hilferty transformation using tabulated correction factors to extend the useful range of skewnesses to nine and greater.

Thomas and Fiering (44) approached the generation of streamflows for a system of rivers by choosing a central station and using regression coefficients to generate flows at the other stations based upon the generated flow at the central station. A defect of this model is that it cannot account for the correlation between flows in successive months, i.e., the serial correlation, at the outlying streamflow stations. (8)

Fiering (8,18) later presented a method for generating streamflows for systems of streams, or multi-variate streamflow, using principal component analysis, which eliminated most of the problems with the earlier method.

N. C. Matalas (28) proposed another technique for multi-variate synthetic streamflow which overcame the remaining problems of the Fiering technique. In this model, generating matrices were calculated from the historical flows by principal component analysis and were then used to generate vectors of flow deviation from the mean flow for the month. The synthetic streamflows were then formed by adding the mean flow for the month.

G. K. Young and W. C. Pisano (51) modified and simplified the Matalas model by eliminating the need to use principal component analysis to calculate the generating matrices. They further simplified the model by the use of residuals, deviations from the mean flow divided by the standard deviation. This reduced the magnitude of the numbers involved.

Extensive work has been done in the last few years on "non-markovian" streamflow generation techniques capable of producing more realistic persistence, or serial correlation, in the generated flows.

J. R. Wallis and N. C. Matalas (48,49) have been active in the development of Fractional Gaussian Noise generation models. Jose M. Mejia, L Rodriguez-Iturbe, and David Dawdy (32,41) have been developing "Broken Line" process techniques for streamflow generation.

In many cases, streamflow records are either too short for calculation of generation coefficients, are non-existent, or have been made unsuitable for most synthesis models by man's actions to regulate the stream. Benson and Matalas (2) have devised a technique called regionalization for estimating unknown streamflow statistics by multiple regression methods from the statistics of nearby or similar streams. R. L. Pentland and D. R. Cuthbert (35) combined regionalization with a "grid square technique" to develop synthetic streamflow models for several ungauged watersheds in New Brunswick.

The objective of these synthesis models is to produce streamflow sequences which contain as many extreme conditions as possible, especially those not contained in the historic record, but which could possibly occur.

III. METHODS OF ANALYSIS

This thesis demonstrates the use of several operations research techniques for the design and operation of water resource systems. The problem chosen is the preliminary design of two reservoirs in the upper James River Basin, with Figure 3-1 being a schematic diagram of the study area. Two Water Quality Control Points (WQCP), Covington and Lynchburg, as well as two reservoirs, Gathright and Hipes, have been designated. Gathright reservoir serves a dual function: it must not only meet the demands of the Covington WQCP, but must also operate in parallel with the Hipes reservoir to meet the Lynchburg demands.

The four streamflow gauging stations shown in Figure 3-1 are on the Jackson River at Falling Spring, Dunlap Creek near Covington, Craig Creek at Parr, and the James River at Holcomb's Rock. Further information on these gauges is given in Table 3-1.

The United States Army Corps of Engineers has published designs for the two reservoirs. Details of these designs are given in Table 3-2.

In this study, the operations of the James River system will be simulated under varying flow conditions to determine preliminary designs which will then be compared with the Corps of Engineers designs. These preliminary designs will be obtained through the use of a stochastic linear programming model. This model is an extension of the single reservoir linear decision rule model developed by Revelle, Joeres, and Kirby (39,40), and determines the optimal design for two reservoirs operating in parallel to meet demands. The designs produced by the model consist of the required storage capacities along

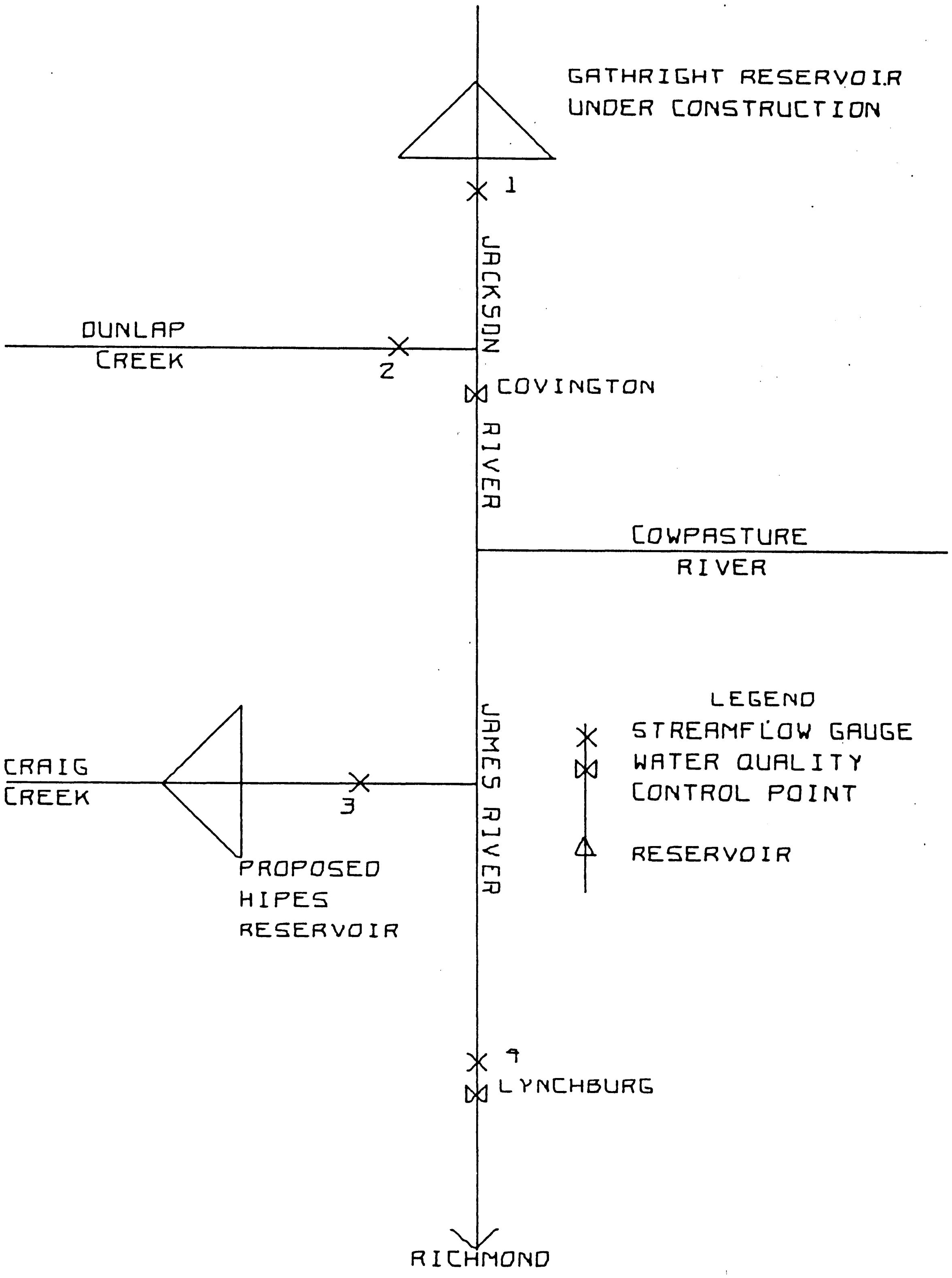

FIGURE 3 . 1 SCHEMATIC OF UPPER JAMES RIVER BASIN

TABLE 3-1

STREAMFLOW GAUGING STATIONS USED IN STUDY

Gauge Number	Station Name and Location	Drainage Area (Sq. Mi.)	Length of Record	Mean Daily Flow (cfs)
1	Jackson River at Falling Springs	409	1925-1973	476
2	Dunlap Creek near Covington	166	1928-1973	157
3	Craig Creek at Parr	331	1925-1973	370
4	James River at Holcomb's Rock	3463	1926-1972	3,463

After U. S. Army Corps of Engineers, DEVELOPMENT OF WATER RESOURCES IN APPALACHIA (45).

TABLE 3-2

ELEMENTS OF CORPS OF ENGINEERS DESIGNS FOR HIPES AND GATHRIGHT RESERVOIRS

	Gathright	Hipes
Storage Volumes (in thousands of acre feet)		
Total Pool	203.6	304.7
Flood Control Pool	79.9	73.3
Minimum Pool	63.0	115.7
Conservation Pool (Active Storage)	60.7	115.7
Drainage Area above Dam (in Sq. Mi.)	344.0	327.0

After U. S. Army Corps of Engineers, DEVELOPMENT OF WATER RESOURCES IN APPALACHIA (45).

with a set of monthly operating rules. A satisfactory design will ensure monthly flows sufficient to maintain a dissolved oxygen (D.O.) concentration of 5.0 milligrams per litre (mg/l) at each WQCP with a failure rate no greater than one month in two hundred and forty months (twenty years). (46) Flows necessary to maintain the D.O. level at each WQCP have been determined by the Environmental Protection Agency (EPA) for the years 1980, 2000, and 2020, based upon projected waste loads in the upper James River. These projections have assumed 85%, 90%, 95%, or 98% removal of five day Biochemical Oxygen Demand (BOD_5). (30) Table 3-3 shows the total waste loads projected by the EPA and the Virginia Division of Water Resources. Tables A1-1 to A1-4 in Appendix 1 list the flows required at each WQCP in each month for each BOD_5 removal rate. (30)

Unfortunately, the allowed failure rate of one month in two hundred and forty for the James River Basin is not in the form required by the linear decision rule model, which requires individual allowable failure rates for each month of the year. For example, a demand may be allowed a failure rate of 50% in February and 10% in July. Since the calculation of allowable monthly failure rates which satisfy the overall allowed frequency is currently intractable, initial estimates of failure frequencies are arbitrarily made for each month. The resultant design is evaluated by simulation using synthetically generated streamflow. If the design is satisfactory, the preliminary stage of the design process is complete. However, if the design is unsatisfactory, the monthly failure rates must be modified at each

TABLE 3-3

TOTAL PROJECTED WASTE LOADS* FOR THE UPPER JAMES RIVER BY ENVIRONMENTAL PROTECTION AGENCY AND VIRGINIA DIVISION OF WATER RESOURCES

Year	EPA (FWPCA)	VDWR
1980	406,365	418,790
2000	492,310	910,930
2020	947,660	1,716,790

* in pounds of BOD_5 prior to treatment

After McGee, Personal Communication (30).

WQCP where the standard was violated. The design and evaluation stage is repeated until a satisfactory design is either found or shown to be unattainable.

Unattainability follows from the fact that monthly failure rates are percentiles of the observed monthly distributions of flows. Although interpolation between observed percentiles is reliable, extrapolation outside the range of observed data can be highly unreliable and is not done in this study. Obviously, this practice limits the useable range of monthly failure frequencies to the percentiles of the observed maximum and minimum flows. If a satisfactory design cannot be found using this range of frequencies, the design process ends without determining a preliminary design for the system.

The first step in evaluating a design is to simulate its operations with several sets of synthetic streamflow. Next, the average D.O. failure rate for each WQCP is calculated, along with its standard deviation. These statistics are then used to test the hypothesis that the overall failure rate for each WQCP is less than or equal to the allowable rate. For the test used, the probability of rejecting a satisfactory design is .01, or one percent. An equal concern is the probability of accepting an unsatisfactory design. Since most of the unsatisfactory designs have overall failure rates considerably higher than the allowable failure rate, these are easily rejected. However, some unsatisfactory designs have failure rates which are extremely close to the allowable rate. In this study, if an unsatisfactory design has an average failure rate at least one standard deviation away from the allowable rate, there is a probability of .96 that it will be properly rejected as an unsatisfactory design. This required twenty simulation runs per design evaluation.

The remainder of this chapter will be concerned with the development of the linear decision rule model and the synthetic streamflow generator for the James River system.

Linear Decision Rule Model

The linear decision rule model of Revelle, *et al.*, is a straightforward means of determining designs for a single reservoir using a linear program to optimize the design and operation of the reservoir. The objective function used in this study is the minimization of total storage capacity in the two reservoir systems. This is considered a reasonable approximation of the desired minimization of construction costs because of the similar terrain in which the two dams are to be built.

The following notations will be used in defining the problem:

G - Gathright prefix

H - Hipes prefix

t - Consecutive index over all months, $t = 1, \ldots$

i - Cyclic index over calendar months, $i = 1, \ldots, 12$

Q_t - Natural flows in month t

B_i - Release parameter in month i

F_i^Q - Cumulative distribution function of flows Q in month i

X_t - Release in month t

S_t - Storage at end of month t

α - Minimum acceptable probability of satisfying a performance constraint, $0 \leq \alpha \leq 1$

$R_i^{Q,\beta}$ - β - percentile of the observed flows, Q, in month i

p - probabilistic constraint suffix

d - deterministic constraint suffix

Cov - Covington subscript

Lyn - Lynchburg subscript

CAP - Reservoir Capacity

FCP - Flood Control Pool

Am - Fraction of capacity equal to minimum volume

Ao - Fraction of capacity equal to original volume at time t = 0

MV - Minimum volume, MV = AM * CAP

FF - Minimum Flood Flow

CC - Craig Creek suffix

DC - Dunlap Creek suffix

JK - Jackson River suffix

JR - James River at Holcomb's Rock suffix

The problem to be solved can now be formally stated as

MINIMIZE HCAP + GCAP

Subject to the following performance constraints,

1. The end of month storage shall be below a flood buffer level with probability α_1. The flood buffer level is the capacity minus the flood control pool volume.

$$Pr(S_t \leq CAP - FCP) \geq \alpha_1 \qquad [1]$$

2. The release in month t shall be less than the minimum flood flow with probability α_2.

$$Pr(X_t \leq FF) \geq \alpha_2 \qquad [2]$$

3. The storage at the end of month t shall be above the minimum volume with probability α_3, where MV = Am * CAP.

$$PR(S_t \geq MV) \geq \alpha_3 \qquad [3]$$

4. The release in month t shall be non-negative with probability α_4.

$$Pr(X_t \geq 0) \geq \alpha_4 \qquad [4]$$

5. The water requirements at WQCP's in month t shall be met with probability α_5.

$$Pr(Q_{WQCP,t} \geq EME_{WQCP,i}) \geq \alpha_5 \qquad [5]$$

Constraints one and two represent flood control. Constraint one requires the end of month storage to be below a specified flood buffer level. Flood buffer level is the reservoir capacity minus the flood control pool volume, where the flood control pool volumes for each reservoir have been specified by the Corps of Engineers and are given in Table 2. (45) The flood buffer level constraints for each reservoir are

a. Gathright

$$Pr(GS_t \leq GCAP - GFCP) \geq \alpha_1 \qquad [1G_p]$$

b. Hipes

$$Pr(HS_t \leq HCAP - HFCP) \geq \alpha_1 \qquad [1H_p]$$

Constraint two requires the release for each month to be less than the minimum flood flow. The probability of a month's release being larger than the minimum flood flow over an entire month is minimal, so this constraint, in all likelihood, will be redundant. The flood flow constraints for each reservoir follow:

a. Gathright

$$Pr(GX_t \leq GFF) \geq \alpha_2 \qquad [2G_p]$$

b. Hipes

$$Pr(HX_t \leq HFF) \geq \alpha_2 \qquad [2H_p]$$

The minimum flood flows below each reservoir are also given in Table 2. For this study, the allowable monthly failure rate for these constraints has arbitrarily been set at 10%. The flood control operation of each reservoir on a monthly time scale is assumed to be independent.

By setting a minimum storage level, constraint three represents outdoor recreation, fish and wildlife enhancement, and general esthetic values. Storage levels lower than normal adversely affect recreational benefits (33). Fish and wildlife are affected by the disruption and destruction of feeding and breeding areas at low water levels, while exposed bottom detracts from the scenic appeal of the reservoir. The minimum volume fractions of capacity used in this study are the same as those used by the Corps of Engineers in their designs for the Hipes and Gathright reservoirs. In this paper, the allowable monthly failure rate for this constraint has been set at 10%. The two constraints are as follows:

a. Gathright

$$Pr(GS_t \geq GAm * GCAP) \geq \alpha_3 \qquad [3G_p]$$

b. Hipes

$$\Pr(HS_t \geq HAm * HCAP) \geq \alpha_3 \qquad [2H_p]$$

Constraint four requires non-negative releases. The allowable failure rate was set as low as the available data would permit, 2.5%. These constraints are

a. Gathright

$$\Pr(GX_t \geq 0) \geq \alpha_4 \qquad [4G_p]$$

b. Hipes

$$\Pr(HX_t \geq 0) \geq \alpha_4 \qquad [4H_p]$$

The water supply demands used for constraints five are the flows necessary to maintain the D.O. standard at each WQCP (30). Other water requirements, such as municipal water supply and irrigation, are either insignificant or can be met by the augmented flow (45). An initial monthly failure rate of 10% is used for each water supply constraint. If this monthly rate does not yield a satisfactory overall rate, a smaller monthly rate must be used for each WQCP which failed. The WQCP constraints are

a. Covington

$$\Pr(Q_{COV,t} \geq DMD_{COV,i}) \geq \alpha_5 \qquad [5C_p]$$

b. Lynchburg

$$\Pr(Q_{Lyn,t} \geq DMD_{Lyn,i}) \geq \alpha_5 \qquad [5L_p]$$

As these constraints are probability statements, this type of programming problem is referred to as a "Chance Constrained" problem. To solve this type of problem by linear programming techniques, the constraints must first be converted to an equivalent deterministic form. This is done with the aid of the linear decision rule upon which the model is based.

The linear decision rule states that the release in month t, X_t, is found by subtracting a release parameter for the calendar month, B_i, from the storage at the end of the previous month, S_{t-1}. This is expressed as

$$X_t = S_{t-1} - B_i \qquad \begin{array}{l} t = 1, \ldots, \text{number of months in study} \\ i = 1, \ldots, 12 \\ i \text{ is cyclic in each year} \end{array} \tag{6}$$

Saying that i is cyclic in each year means that t corresponds with any calendar month i when t equals i plus a multiple of 12.

A continuity relationship between storages in succeeding months, the release in a month, and the inflow in a month, Q_t, can also be specified:

$$S_t = S_{t-1} + Q_t - X_t \tag{7}$$

These relationships will be used to convert stochastic, or probabilistic, constraints of the linear decision rule model to deterministic equivalents. This conversion is accomplished through the use of the observed distributions of flows at the gauging stations in the system.

If releases and storages are not expressed as linear functions of release parameters only, the distributions of storages would also be required. These distributions are not available at this stage of the design process. Therefore, storages are expressed as a function of inflows and release parameters by substituting equation 6 into 7. The result is

$$S_t = Q_t + B_i \qquad [8]$$

Next substitute equation 8 into 6. The result,

$$X_t = Q_{t-1} + B_{i-1} - B_i, \qquad [9]$$

expresses the release as a function of inflows and release parameters.

Constraint one for the Gathright reservoir requires that the end of month storage be below the flood buffer level with probability α_1,

$$\Pr\ (GS_t \leq GCAP - GFCP) \geq \alpha_1 \qquad [1G_p]$$

This can be expanded by equation 8 to

$$\Pr\ (QJK_t \leq GCAP - GFCP - GB_i) \geq \alpha_1$$

For this statement to hold, the quantity $(GCAP-GFCP-GB_i)$ must be greater than some value, say R_i^{JK,α_1}, which is greater than or equal to $(\alpha_1 * 100)\%$ of all observed flows, QJK_t, $t = 1, \ldots,$ (number of observed flows). This is stated as

$$GCAP - GFCP - GB_i \geq R_i^{JK,\alpha_1}$$

or

$$GCAP - GB_i \geq GFCP + R_i^{JK,\alpha_1} \qquad [1G_d]$$

This is the deterministic equivalent of the original probabilistic constraint. The remaining constraints for Gathright and Hipes are converted in the same fashion.

Constraint five for the Lynchburg and Covington WQCP's is complicated by the combinations of regulated and unregulated flows which make up the total flow past each WQCP. To handle this situation, combinations of unregulated flows and the observed distributions of these combinations must be used.

The flow past Covington is a combination of the Gathright release and the Dunlap Creek flow,

$$Q_{Cov,t} = GX_t + QDC_t .$$

The use of equation 9 to expand the Covington water supply constraint, equation 5C yields

$$\Pr(QJK_t + GB_{i-1} - GB_i + QDC_t \geq DMD_{Cov,i}) \geq \alpha_5 \qquad [5C_p]$$

A random variable, the combination of Jackson River flows in month t-1 and Dunlap Creek flows in month t, QCl_t, can now be defined as:

$$QCl_t - QJK_{t-1} + QDC_t .$$

Rearranging the above probability statement to put the random flow terms on the left yields

$$\Pr\ (QCl_t \geq DMD_{Cov,i} - \{GB_{i-1} - GB_i\}) \geq \alpha_5$$

This can also be stated as

$$\Pr\ (QCl_t \leq DMD_{Cov,i} - \{GB_{i-1} - GB_i\}) \leq 1 - \alpha_5 .$$

For this statement to be true, there must be some value, say $R_i^{Cl,1-\alpha_5}$. which is greater than or equal to $(1-\alpha_5 *100)\%$ of the observed QCl 'flows' and, at the same time, is greater than the quantity $[DMD_{Cov,i} - (GB_{i-1} - GB_i)]$. This can be stated as

$$R_i^{Cl,1-\alpha_5} \geq DMD_{Cov,\ i} - (GB_{i-1} - GB_i).$$

This can be rearranged to yield the deterministic equivalent of $5C_p$,

$$GB_{i-1} - GB_i \geq DMD_{Cov,i} - R_i^{Cl,1-\alpha_5} \qquad [5C_d]$$

In the initial month of the study, $(t = i = 1)$, the linear decision rule must be used to determine the release instead of equation 9. Consequently, a different constraint is needed for this month. The release plus the flow greater than $(1-\alpha_5 *100)\%$ of Dunlap Creek flows must be greater than or equal to the demand,

$$GX_1 + R_1^{DC,1-\alpha_5} \geq DMD_{Cov,1}$$

This can be rearranged and expanded to yield the following constraint for month $t = i = 1$:

$$Ao * GCAP - GB_1 \geq DMD_{Cov,1} - R_1^{DC,1-\alpha_5}$$

In a similar fashion, but with two reservoirs, the Lynchburg water requirements constraint may be developed from equation 5L. With Gathright and Hipes reservoirs in operation, the flow at Lynchburg is equal to the natural flow at Lynchburg plus the excess of release over inflow or minus the deficiency of inflow from release at each reservoir. This is stated as

$$Q_{Lyn,t} = QJR_t + (GX_t - QJK_t) + (HX_t - QCC_t)$$

After inserting this statement for $Q_{Lyn,t}$ into constraint $5L_p$ and expanding the release terms in accordance with equation 9, the constraint becomes

$$\begin{aligned} Pr\ (QJR_t + QJK_{t-1} + GB_{i-1} - GB_i - QJK_t + QCC_{t-1} + HB_{i-1} \\ - HB_i - QCC_t \geq DMD_{Lyn,i}) \geq \alpha_5 \end{aligned} \qquad [5L_p]$$

By defining another combination of flows,

$$QC2_t = QJR_t + QJK_{t-1} - QJK_t + QCC_{t-1} - QCC_t,$$

and collecting random terms on the left hand side of the probability statement, 5L, the constraint may now be stated as

$$\Pr\left(QC2_t \geq DMD_{Lyn,i} - \{GB_{i-1} - GB_i + HB_{i-1} - HB_i\}\right) \geq \alpha_5$$

Using the same logic as with the Covington constraint, the deterministic equivalent of the Lynchburg constraint may be stated as

$$GB_{i-1} - GB_i + HB_{i-1} - HB_i \geq DMD_{Lyn,i} - R_i^{C2,1-\alpha_5} \qquad [5L_d]$$

For the initial month of operation, t = i = 1, the following constraint applies:

$$Ao * GCAP - GB_1 + Ao * HCAP - HB_1 \geq DMD_{Lyn,1}$$

$$- R_1^{(QJR + QCC + QJK),1-\alpha_5}$$

When all constraints have been converted in the manner described, the original probabilistic problem can be expressed in the following equivalent deterministic form.

MINIMIZE HCAP + GCAP

Subject to,

1. Flood buffer level

   a. Gathright

   $$HCAP - HB_i \geq R_i^{JK,.9} + HFCP \qquad [1G_d]$$

   b. Hipes

   $$GCAP - GB_i \geq R_i^{CC,.9} + GFCP \qquad [1H_d]$$

2. Flood flow

$$GB_{i-1} - GB_i \leq GFF - R_{i-1}^{JK,.9} \qquad [2G_d]$$

a. Gathright

$$GAo * GCAP - GB_1 \leq GFF, \qquad i=t=1$$

b. Hipes

$$HB_{i-1} - HB_i \leq HFF - R_{i-1}^{CC,.9}$$

$$GAo * HCAP - HB_1 \leq HFF, \qquad i=t=1 \qquad [2H_d]$$

3. Minimum volume

a. Gathright

$$GAm * GCAP - GB_i \leq R_i^{JK,.1} \qquad [3G_d]$$

b. Hipes

$$HAm * HCAP - HB_i \leq R_i^{CC,.1} \qquad [3H_d]$$

4. Non-negative releases

a. Gathright

$$GB_i - GB_{i-1} \leq R_i^{JK,.025}$$

$$GB_1 - GAo * GCAP \leq 0, \qquad i=t=1 \qquad [4G_d]$$

b. Hipes

$$HB_i - HB_{i-1} \leq R_i^{CC,.025}$$

$$HB_1 - HAo * HCAP \leq 0, \qquad i=t=1 \qquad [4H_d]$$

5. Water requirements at WQCP's

a. Covington

$$GB_{i-1} - GB_i \geq DMD_{Cov,i} - R_i^{C1.,1}$$

$$GAo * GCAP - GB_1 \geq DMD_{Cov,1} - R_1^{DC.,1} \qquad i=t=1 \qquad [5C_d]$$

b. Lynchburg

$$GB_{i-1} - GB_i + HB_{i-1} - HB_i \geq DMD_{Lyn,i} - R_i^{C2.,1} \qquad [5L_d]$$

$$GAo * GCAP - GB1 + HAo * HCAP - HB1 \geq DMD_{lyn,1} - R_1^{(JR+CC+JK),1-\alpha_5} \qquad i=t=1$$

GB_i, HB_i unrestricted in sign, $i = 1, \ldots, 12$

$GCAP, HCAP \geq 0$

The flood flow and water supply constraints create necessary conditions for the existence of feasible solutions to the linear programming problem (39). This can be demonstrated for the Covington water supply constraint by summing equation $5C_d$, the Covington constraint, over the calendar month index, i. Because of the cyclic nature of the release parameters, B_i, the sum of (B_i-1 - B_i) over a year is zero. Upon proper rearrangement of the sum, the following necessary condition for feasible solutions is seen to exist.

$$\sum_{i=1}^{12} R_i^{C1,1-\alpha} \geq \sum_{i=1}^{12} DMD_{Cov,i}$$

This condition states that for a feasible solution to exist, the sum of the monthly Covington demands must be less than the sum of the 1-α percentile flows of combination one in each month. A similar condition exists for the sum of the Lynchburg demands and the percentiles of combination two flows.

By summing the flood flow constraints over the calendar months, it can be shown by the same reasoning that another necessary condition for feasible solutions is that the sum of the α_2 percentile flows for each month be less than the sum of the minimum flood flows,

$$\sum_{i=1}^{12} R_i^{Q,\alpha 2} \leq \sum_{i=1}^{12} FF$$

Results of the search for an optimal design for the James River system are given in Chapter IV.

Synthetic Streamflow Generation

The synthetic streamflow model used in this study is based upon the Young-Pisano (51) model, with a modification based upon a Corps of Engineers model (46). Recall from chapter II that regression coefficients must be calculated from the historic record for use in the model. A primary consideration in the calculation of these coefficients is the correlation between flows in different months at each station. Figure 3-2 is a correlogram of the correlation between flows in the Jackson River from 1931 to 1970 separated by lags of varying numbers of months. As can be seen, there is significant positive correlation between flows separated by lags which are multiples of one year. There is also significant negative correlation between flows separated by lags which are multiples of a year plus or minus six months. Taking these correlations into account in the generation of synthetic streamflows would be extremely complicated. To avoid this problem, Matalas (28), Young and Pisano (51), and the Corps of Engineers (46), use the method of residuals.

A residual is the remainder, or "residue", when the average of a variable, $\overline{X}$, has been subtracted from a value of the variable, X, and the result divided by the standard deviation of the variable, S_x,

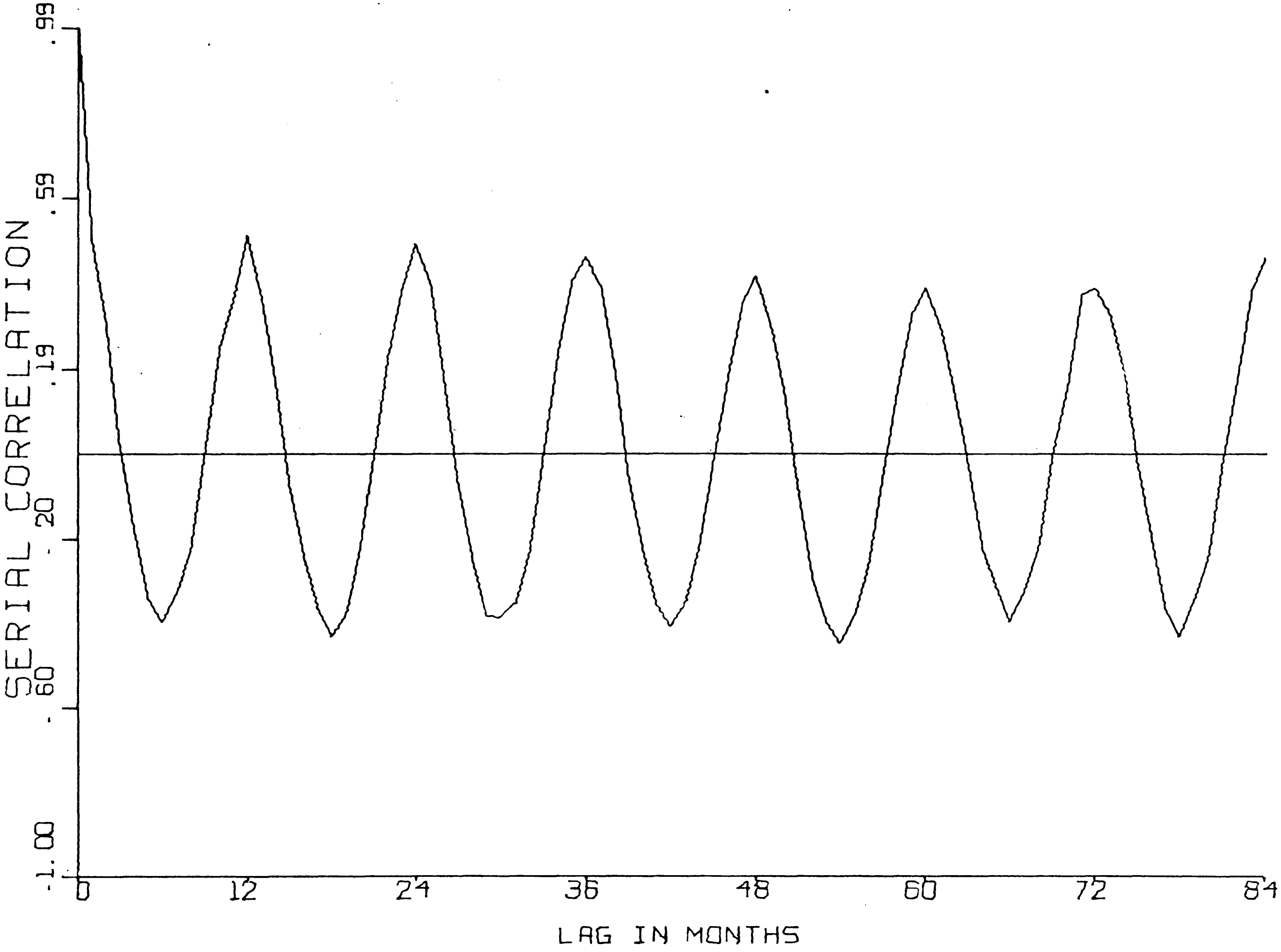

FIGURE 3 - 2 SERIAL (LAGGED) CORRELATION BETWEEN FLOWS IN THE JACKSON RIVER

$$R = \frac{(X - \overline{X})}{S_x}$$

When a correlogram for the residuals of the flows in the Jackson River is plotted, Figure 3-3, the significant correlation effects are no longer present. This suggests that the generation of synthetic residuals based on the historic residuals, followed by reconstruction of flows from the synthetic residuals by a transformation of the type

$$X = S_x * R + \overline{X},$$

is less complicated or more manageable method. This is what the Young-Pisano and Corps of Engineers models do.

In the Young-Pisano model, the historic residuals are assumed to be related by the expression

$$\underline{R}_t = \underline{A} * \underline{R}_{t-1} + \underline{B} * \underline{e}_t \qquad [10]$$

Where $\underline{R}_t$ is an n x 1 vector of the residuals of the flows at the n stations in the system in month t

e_t is an n x 1 vector of n random independent variates, each normally distributed with a mean of zero and a variance of one.

A & B are n x n matrices calculated from the historic residuals. The $\underline{A}$ matrix relates the flows in month t with those in month t-1 at each site and between sites. The $\underline{B}$ matrix transforms the independent vector, $\underline{e}_t$, into a correlated random vector with the characteristics of the historic residuals.

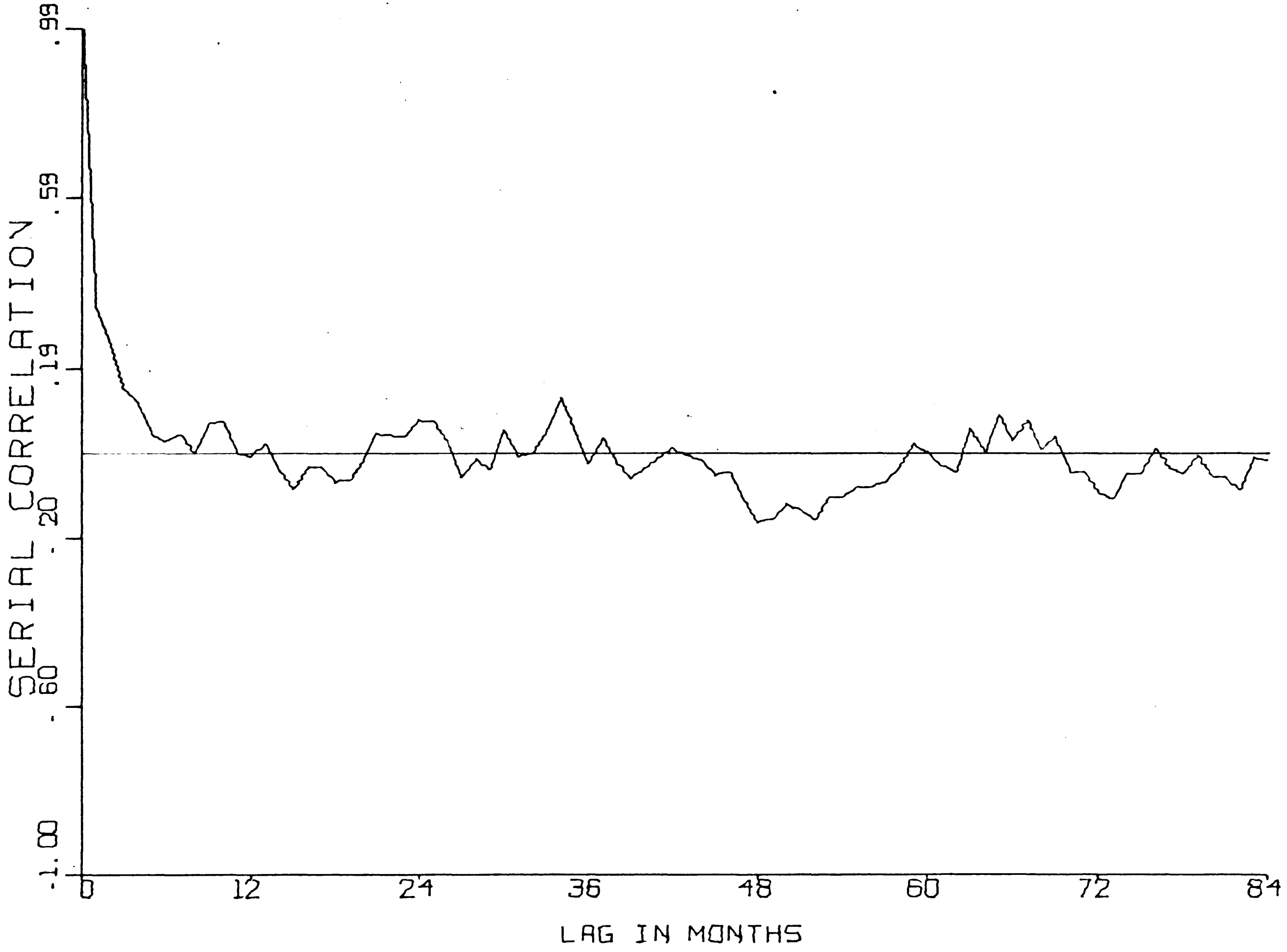

FIGURE 3 - 3 SERIAL (LAGGED) CORRELATION BETWEEN-
FLOW RESIDUALS IN THE JACKSON RIVER

Detailed instructions for calculating $\underline{A}$ and $\underline{B}$ from the historic residuals may be found in Young and Pisano's paper (51). James and Pegram (34) have extended the Young and Pisano model to include cases where flows in a month are considered to depend upon flows in several preceding months.

The use of residuals for generating streamflow by the Young-Pisano method makes two important assumptions. The first is that the generation of residuals, followed by the construction of flows from the residuals, not the generation of flows themselves, is a satisfactory model. Second is that one can average the correlations between flows over the entire year to form $\underline{A}$ and $\underline{B}$ matrices which will generate flows in all months. This last assumption is evident in the calculation of $\underline{A}$ and $\underline{B}$ by the method given in Young and Pisano's paper. If correlations between stations in the same or preceding months are significantly different from the average correlation used in the model, the synthetic flows may not satisfactorily reproduce the characteristics of the historic flows.

The steps in the generation of synthetic streamflows by the Young-Pisano model are as follows:

1. Calculate the residuals of the historic flows. This is done by first calculating the average and standard deviation of the flows for each month at each station to be simulated. The following expression is then used to calculate the residuals:

$$R^j_{kt} = \frac{(Q^j_{kt} - \overline{Q}^j_{kt})}{S^j_{kt}} \qquad \begin{array}{l} j=1,\ldots,\ \text{number of streamflow stations} \\ k=1,\ldots,\ 12\ \text{(calendar months)} \\ t=1,\ldots,\ \text{number of months of record} \end{array}$$

2. Calculate the generation matrices, $\underline{A}$ and $\underline{B}$, from the residuals.

3. Assume a starting residual vector ($\underline{R} = \underline{0}$ is a typical choice), and use the $\underline{A}$ and $\underline{B}$ matrices to generate a sequence of residuals of any desired length.

4. Transform the residuals to flows.

Because the generating equation, 10, uses the normal distribution for the random component of each new vector of residuals, the generated residuals and resulting flows will be normally distributed. However, stream flows in nature are not normally distributed in most months, instead they possess pronounced skewness. Several possible ways exist for generating skewed residuals which will yield property skewed flows. One of these is to use a random vector, $\underline{e}_t$, with skewed components. Another is to transform the skewed historic residuals into a set of residuals having little or no skewness. This is done with the following steps:

1. Transform the skewed historic residuals to a non-skewed form,

$\underline{R} = T(\underline{R}_g)$ where $\underline{R}$ = non-skewed residuals
$\underline{R}_g$ = skewed residuals
T = transformation used

2. Calculate the $\underline{A}$ and $\underline{B}$ matrices from the non-skewed residuals.

3. Generate non-skewed synthetic residuals.

4. Transform these residuals to skewed form by the inverse of the transformation used to remove the skewness from the historic residuals,

$$\underline{R}_g = T^{-1}(\underline{R})$$

Young and Pisano prescribe still another method, where the flows are transformed before forming residuals. Their only specification is that the skewness of the residuals must be of close to zero as possible. They suggest the possibility of taking logarithms or square roots of the flows (51).

An example of a logarithmic transformation of the historic flows can be found in a Corps of Engineers model (46). After this transformation, residuals of the logarithms are found. The remaining skewness is removed from the residuals by the use of the inverse of the Wilson-Hilferty transformation. This transformation was cited by Fiering (9,10) for transforming normal variates to skewed variates, although in this case the transformation is from skewed to normal variates. The Army model uses multiple linear regression in calculating the synthetic residuals. After the synthetic residuals have been calculated, they are transformed to skewed residuals by the Wilson-Hilferty transformation. Three methods of correcting residuals for skewness were used. The first was the use of the inverse Wilson-Hilferty transformation on the residuals of the original flows. The second was a logarithmic transformation of the flows before forming residuals. The third was the use of the inverse Wilson-Hilferty transformation on the residuals of the logarithms.

The inverse Wilson-Hilferty transformation for calculating non-skewed residuals from skewed residuals is as follows:

$$r = (6/g) * \{[(g * (r_g/2)) + 1]^{1/3} - 1\} + g/6$$

where g = skewness of flows in the month at the station of interest

r_g = skewed residual

r = non-skewed residual

The Wilson-Hilferty transformation, used to reconstruct skewed residuals after generation of non-skewed residuals, is

$$r_g = (2/g) * \{(1 + (g * r/6) - g^2/36)^3 - 1\}$$

The method used to generate flows for the evaluation of reservoir system designs is dictated by a subjective comparison of the statistics of the historic and synthetic flows. If one method is the best at reproducing the historic flow characteristics, it is the one to use. However, if several methods reproduce the historic statistics satisfactorily, they should all be used for design evaluation.

To compare the historic and synthetic flows, the following steps are performed.

1. Generate several sequences of synthetic streamflow, by the three methods described.

2. For each sequence, compute the average, variance and skewness of flows in each month at each station. Then compute the overall cross correlations (between stations in a month) and serial correlations (between stations and at stations in successive months).

3. Compute the average value and standard deviation of each statistic calculated for each sequence.

4. Use the standard deviation to place a 99% confidence interval about the average value of each statistic. There is a 99% probability that the true value of the statistic for the sequences lies in this

interval.

5. Make plots of the confidence intervals and the historic statistic values, such as the sample shown in figure 3-4, and count the number of historic statistic values contained in the confidence intervals.

6. Use this information to decide which method, or methods, best reproduce the statistics and other characteristics, such as month to month trends, of the historic flows.

7. Use the best method(s) for the evaluation of the reservoir designs produced by the linear decision rule.

As in the evaluation of a reservoir design, most historic statistics will lie in the interval's bounds, or far away from them. If they lie far away, the hypothesis that the historic and synthetic statistics are equal may be rejected easily. However, some historic statistics which should be rejected may lie close to the confidence interval's bounds, or even within the interval. It was found that using twenty sets of synthetic streamflow gave a probability of .94 that synthetic and historic statistic values at least one standard deviation apart will be properly rejected.

When not using a logarithmic transformation of flows, negative synthetic flow values may be generated.

When this happened, the negative value was given a positive value, a randomly determined fraction of the minimum flow of record for that month and station. The flows of the other stations were then augmented by the same amount.

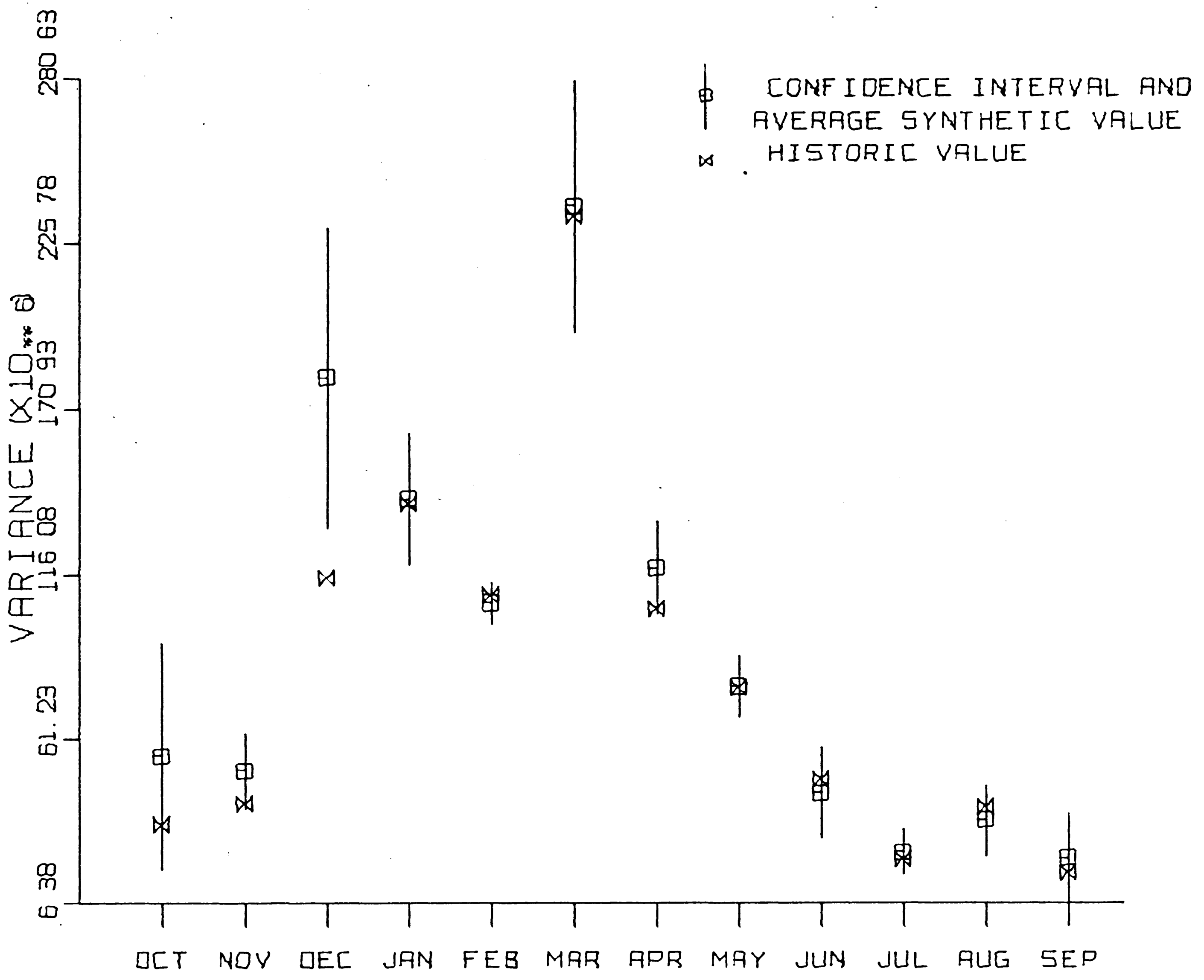

FIGURE 3 - 4 COMPARISON OF SYNTHETIC AND HISTORIC VARIANCE
STATION 1 SYNTHESIS TECHNIQUES USED: LOG -YES. SKEW -YES

The flows generated were stored on magnetic tape or disk for later use in the simulation of the reservoir designs.

Simulation of Reservoir Operations

The simulation phase of the design process evaluates the performance of each reservoir system design in meeting the water quality at the two WQCP's, Covington and Lynchburg. It also determines the monthly and overall frequencies of failure for the constraints imposed by the linear decision rule model. It does this by routing twenty 100-year sequences of streamflow through the proposed system design. At the end of each evaluation, the program calculates the necessary statistics to determine if the design is satisfactory. The probability of rejecting a satisfactory design, i.e., the significance level of the test, was .01 in this study. The corresponding probability of rejecting an unsatisfactory design as close as one standard deviation to the allowed rate is .96.

Each design evaluation requires the design for the system from the linear decision rule model, the flow requirements at Covington and Lynchburg, and twenty sequences of synthetic streamflows. The procedure for the simulation is as follows:

1. Obtain one 100-year flow sequence from the twenty available.
2. For each month, perform the following procedure:

a. From the 100-year sequence in use, obtain the flows for the system for the month.

b. Calculate reservoir releases and end-of-month storages by the linear decision rule for each reservoir. If the rule indicates a negative release or a release less than the minimum flow of record for that month, the program sets the release equal to the minimum flow of record. This is a deviation from the optimal release rule, but it is necessary if the reservoir operations are to be realistic.

c. Check releases and end-of-month storages against all performance constraints except water supply.

d. Calculate the flows at Covington and Lynchburg and check for water supply failure. If the Lynchburg flow is less than the sum of the Hipes release and the Covington flow, it is made equal to that sum before the demands are checked.

3. Calculate the monthly and overall failure frequencies for each performance constraint.

4. If all 100-year sequences have been used, proceed to step 5, otherwise, return to step one for another simulation run.

5. Calculate the average and standard deviation of the overall failure frequencies of the water supply constraints and use these to form the test statistics for the design evaluation.

If the design is satisfactory, the preliminary design phase is complete. If the design is unsatisfactory, the process must be repeated as described earlier.

IV. COMPUTATIONAL RESULTS

Streamflow Synthesis

Three groups of twenty 100 year synthetic streamflow sequences were generated, one by each of the three methods described in chapter III, the Wilson-Hilferty transformation of residuals, the logarithmic transformation of flows, and the combination of Wilson-Hilferty and logarithmic transformations. Confidence intervals were calculated about the average values of the statistics of the snythetic flows, and the numbers of historic statistics lying in the confidence intervals were counted. Plots of confidence intervals and historic statistics, of the type shown in Figure 3-4, were examined to see how well the different generation methods followed the trends of the historic statistics.

Tables A2-1 to A2-15 in Appendix 2 list the historic statistic values, the confidence intervals about the synthetic statistic values, and indicate the failures of the historic statistic values to lie in the confidence intervals. Table 4-1 indicates the number of failures (i.e., where the historic statistics failed to lie in the confidence intervals) for each method. A count is made for each statistic and for all statistics together.

Examination of the plots and tables of the historic and synthetic statistics and confidence intervals led to the conclusion that the combined use of the Wilson-Hilferty and logarithmic transformations produced the best synthetic streamflows for the design evaluations.

TABLE 4-1

EVALUATION OF SYNTHETIC FLOW GENERATION METHODS BY CONFIDENCE INTERVAL COMPARISON: NUMBERS OF FAILURES

STATISTIC	TRANSFORMATION(S) USED LOGARITHMIC AND WILSON-HILFERTY	WILSON-HILFERTY ONLY	LOGARITHMIC ONLY	NUMBER OF COMPARISONS
Mean	1	8	9	48
Variance	7	31	42	48
Skewness	34	18	37	48
Cross Correlation	2	6	4	6
Serial Correlation	12	16	13	16
Overall Failures	56	79	105	166

The combined transformation method resulted in the fewest confidence interval failures for each statistic except skewness. Examination of the confidence interval plots and tables showed that the use of the Wilson-Hilferty transformation alone produced synthetic flows with skewness which most closely followed the historic trends. However, the combined transformations followed the historic skewness trends satisfactorily.

Unfortunately, the historic flow characteristics were not reproduced as well as was expected. Several reasons for this relatively poor performance are possible. First, the difference in size between the drainage areas of the streams simulated might have led to the observed results. The combined drainage areas of the stations on the Jackson River, Dunlap Creek and Craig Creek have a size of 906 square miles. This is less than one-third of the 3643 square miles above the James River gauging station at Lynchburg (Holcomb's Rock). Secondly, the averaging of the monthly serial correlations at each site in calculating the $\underline{A}$ and $\underline{B}$ generating matrices might have caused the poor performance by smoothing the effects of significant differences between monthly and average correlations. Table 4-2 shows the calculated serial correlations at each site between the flows of that month and the month before, and the average correlation for the entire year. As can be seen, significant differences do exist between monthly correlations and the average correlation. A possible means of correcting this effect would be to calculate different $\underline{A}$ and $\underline{B}$ matrices for each month's flows.

TABLE 4-2

MONTHLY AND AVERAGE SERIAL CORRELATIONS AT EACH GAUGING STATION BETWEEN INDICATED AND PREVIOUS MONTHS

MONTH	JACKSON RIVER	DUNLAP CREEK	CRAIG CREEK	JAMES RIVER
OCT	0.093	0.216	0.211	0.206
NOV	0.527	0.573	0.639	0.656
DEC	0.559	0.454	0.601	0.704
JAN	0.545	0.500	0.416	0.629
FEB	0.324	0.383	0.258	0.529
MAR	0.078	0.323	0.355	0.586
APR	-0.034	0.215	0.263	0.567
MAY	0.142	0.236	0.184	0.474
JUNE	0.352	0.500	0.588	0.613
JULY	0.429	0.315	0.361	0.482
AUG	0.451	0.549	0.252	0.406
SEPT	0.287	0.628	0.142	0.224
AVER	0.313	0.408	0.356	0.506

The following modifications to the generating techniques were attempted in an effort to improve the performance:

a. Modify the monthly skewness used in the Wilson-Hilferty transformation to account for serial correlation as described by Fiering. (9,10)

b. Use the square root transformation of the flows rather than the logarithmic transformation. This was suggested by Young and Pisano. (51)

Neither of these modifications improved the performance of the streamflow generation. In fact, both resulted in significantly worse performance. In the case of the modified skewness, the worsened performance could have resulted from the fact that Fiering's modification was intended for single station streamflow generation, while flows for multiple stations were being generated here. No explanation of the square root transform's failure is known other than general unsuitability for this particular data.

In reproducing the historic variances, the use of the combined transformations performed significantly better than the other methods. This is important during simulation of reservoir systems, because, as Fiering points out, storage requirements are dependent upon the difference between the maximum surplus and shortage from mean flow (i.e., the range of the flows), and the average range is a function of the length of record and the variance of the flows.

Linear Decision Rule Results and Design Evaluations

A satisfactory reservoir system would be designed to meet demands for the entire projection period, i.e., to the year 2020. Designs should, however, not be neglected for the other two projection years, 1980 and 2000. The primary reason is because there might not be a satisfactory design for the year 2020. In that case it would be necessary to know how long the standards could be met and, when they cannot be met, to know how severely they would be violated. A second reason is because the storage required may grow with time, indicating the possibility of staged construction.

Demands, years, and BOD_5 removal rates are referred to by a one letter, three digit code as follows:

Letter: Source of waste projection

- U - By U. S. Government (EPA)
- V - By Virginia Division of Water Resources (VDWR)

First digit: Year of projection

- 8 - 1980
- 0 - 2000
- 2 - 2020

Second and Third digits: BOD_5 removal rate

- 85 - 85% removal
- 90 - 90% removal
- 95 - 95% removal
- 98 - 98% removal

For example, the system demands and design based upon the EPA projection for the year 2000 with 98% BOD_5 removal would be coded as U098. The demands and design based upon the Virginia projection for the year 1980 with 95% BOD_5 removal would have a code of V895. The unit of volume used in the designs for storages and releases is thousands of acre-feet.

Design Set 1

The first set of designs from the linear decision rule model was obtained using the monthly failure frequencies given in chapter III (2.5% probability of failure of the non-negative release constraint for each month and 10% probability of failure for the other constraints in each month). Table 4-3 lists the resulting designs. Of twenty-four demand sets tried, only seven yielded feasible solutions, i.e., the river system's flows could satisfy the failure rate requirements in only seven of the twenty-four demand sets. In most cases this was due to the sum of the water supply requirements being greater than the sum of the 10th percentile flows being used for this first attempt. It should be noted that in no case was a demand involving 85% or 90% BOD_5 removal able to be met. All feasible designs required 95% or 98% BOD_5 removal. For the U. S. projections, 95% BOD_5 removal was acceptable for 1980 and 2000, but only 98% removal yielded a design for the year 2020. The only projection year for which the Virginia demands could be met was 1980. Table 4-4 shows the maximum required flows at each WQCP in each projection year for each BOD_5 removal rate.

With the 10% monthly failure rate allowed for water quality requirements, the greatest demands which could be met were between 225 and 240 cubic feet per second (cfs) at Covington and between 1100 and 1350 cfs at Lynchburg. The sizes of the Gathright and Hipes

TABLE 4 - 3
LINEAR DECISION RULE DESIGNS FOR SET 1

DESIGN VARIABLE	MONTH	DEMAND SETS V895	V898	U895	U898
GCAP		230.98	230.98	266.34	266.34
GB1	OCT	71.53	71.77	85.93	85.93
GB2	NOV	70.16	70.40	80.84	80.84
GB3	DEC	65.53	65.53	76.50	76.50
GB4	JAN	62.49	62.49	74.11	74.11
GB5	FEB	65.57	65.57	73.70	73.70
GB6	MAR	41.35	41.35	76.72	76.72
GB7	APR	57.09	57.09	92.46	92.46
GB8	MAY	67.54	67.54	102.91	102.91
GB9	JUNE	73.14	73.14	108.51	108.51
GB10	JULY	74.86	74.98	104.71	104.71
GB11	AUG	74.14	74.38	98.46	98.46
GB12	SEPT	73.18	73.42	92.32	92.32
HCAP		207.23	207.23	207.23	207.23
HB1	OCT	76.29	76.29	76.29	76.29
HB2	NOV	80.18	80.18	75.78	75.78
HB3	DEC	84.06	84.06	75.20	75.20
HB4	JAN	79.61	79.61	79.61	79.61
HB5	FEB	76.14	76.14	76.14	76.14
HB6	MAR	60.44	60.44	60.44	60.44
HB7	APR	70.26	70.26	70.26	70.26
HB8	MAY	87.02	87.02	87.02	87.02
HB9	JUNE	96.77	96.77	88.86	74.22
HB10	JULY	102.88	102.88	91.48	80.32
HB11	AUG	95.43	107.09	79.94	84.54
HB12	SEPT	92.57	111.35	76.45	88.79

TABLE 4 - 3
LINEAR DECISION RULE DESIGNS FOR SET 1
(CONTINUED)

DESIGN VARIABLE	MONTH	DEMAND SETS U095	U098	U298
GCAP		271.38	267.65	267.65
GB1	OCT	87.49	86.33	86.33
GB2	NOV	82.40	81.24	81.24
GB3	DEC	78.06	76.90	76.90
GB4	JAN	75.67	73.86	73.86
GB5	FEB	78.74	75.01	75.01
GB6	MAR	81.76	78.02	78.02
GB7	APR	97.49	93.76	93.76
GB8	MAY	107.95	104.22	104.22
GB9	JUNE	113.29	109.81	109.81
GB10	JULY	107.17	105.71	105.71
GB11	AUG	100.32	99.16	99.16
GB12	SEPT	94.18	93.02	93.02
HCAP		262.13	207.23	207.23
HB1	OCT	97.76	106.65	106.65
HB2	NOV	96.64	75.78	75.78
HB3	DEC	96.07	75.20	75.20
HB4	JAN	94.23	73.37	73.37
HB5	FEB	93.24	68.67	68.67
HB6	MAR	97.93	60.44	60.44
HB7	APR	125.16	67.30	70.26
HB8	MAY	141.91	84.05	87.02
HB9	JUNE	147.22	93.81	96.77
HB10	JULY	138.34	99.91	102.34
HB11	AUG	113.59	104.13	100.11
HB12	SEPT	97.31	108.38	103.01

TABLE 4-4

MAXIMUM DAILY FLOW REQUIREMENTS (IN CFS) FOR EACH DEMAND SET

	LYNCHBURG			COVINGTON		
RELATIVE RANK	DEMAND SET	COVINGTON RANKING	DEMAND IN CFS	DEMAND SET	LYNCHBURG RANKING	DEMAND IN CFS
1	V285	1	26600	V285	1	1225
2	V290	3	12700	U285	4	910
3	V085	5	8500	V290	2	860
4	U285	2	8416	U290	6	630
5	U085	6	4260	V085	3	620
6	U290	4	4200	U085	5	555
7	V090	9	4050	V295	8	552
8	V295	7	3500	V298	17	548
9	U885	11	2730	V090	7	430
10	U090	10	2270	U090	10	385
11	V885	13	2000	U885	9	365
12	U890	15	1570	U295	13	330
13	U295	12	1540	V885	11	263
14	V095	14	1425	V095	14	260
15	V890	22	1350	U890	12	250
16	U095	17	1100	V098	21	240
17	V298	8	1100	U095	16	225
18	U895	20	870	U098	22	220
19	U298	19	720	U298	19	220
20	V895	23	710	U895	18	215
21	V098	16	625	U898	24	215
22	U098	18	510	V890	15	168
23	V898	24	300	V895	20	123
24	U898	21	290	V898	23	121

After McGee, Personal Communication (30) reservoirs in the feasible designs did not grow enough over the projection period to warrant the use of staged construction.

Upon evaluation, only the U898, U098, and V898 designs proved to be satisfactory for the Lynchburg WQCP. None of the designs were satisfactory for the Covington WQCP. Table 4-5 lists the average failure frequencies for the water quality flow requirements, the standard deviation of the failure frequencies for the simulation runs, and the test statistic used to evaluate each design. The maximum allowable failure frequency, corresponding to a failure in one month out of each two hundred and forth months, is 0.00417. The maximum satisfactory test statistic is 2.539, where a value greater than this indicates an unsatisfactory design.

Design Set 2

Because the water quality failure rates for Covington in all years and Lynchburg in 2020 were from three to ten times greater than the allowed rate in design set 1, design set 2 used an allowed water quality constraint monthly failure rate of 2.5% for both Lynchburg and Covington.

In this set, only two feasible designs resulted, V895 and V898. These are shown in Table 4-6. This indicated that these were the only demands that could be met with the combination of allowed monthly failure rates used in the run. Table 4-7 shows that the V898 design was satisfactory for Lynchburg, but not for Covington. The V895 design was not satisfactory for either WQCP.

TABLE 4- 5

DESIGN EVALUATIONS FOR SET 1

DEMAND SET	WQCP	FAILURE RATE AVERAGE	STD.DEV.	TEST STATISTIC	SATISFACTORY
V895	COVINGTON	0.03350	0.00630	20.71199	NO
	LYNCHBURG	0.02170	0.00472	16.08739	NO
V898	COVINGTON	0.03358	0.00632	20.81898	NO
	LYNCHBURG	0.0	0.0	************	YES
U895	COVINGTON	0.05117	0.00944	22.26900	NO
	LYNCHBURG	C.C2040	0.00523	16.99016	NO
U898	COVINGTON	0.05117	0.00944	22.26929	NO
	LYNCHBURG	0.0	0.0	************	YES
U095	COVINGTON	0.04787	0.00873	22.38974	NO
	LYNCHBURG	0.03562	0.00618	22.77501	NO
U098	COVINGTON	0.05162	0.00967	21.95200	NO
	LYNCHBURG	0.00104	0.00074	-19.73491	YES
U298	COVINGTON	0.05162	0.00967	21.95200	NO
	LYNCHBURG	0.01487	0.00328	14.59097	NO

TABLE 4 - 6
LINEAR DECISION RULE DESIGNS FOR SET 2

DESIGN VARIABLE	MONTH	DEMAND SETS	
		V895	V898
GCAP		251.78	237.08
GB1	OCT	75.68	71.12
GB2	NOV	73.77	69.21
GB3	DEC	71.98	67.42
GB4	JAN	71.45	66.89
GB5	FEB	63.60	59.05
GB6	MAR	62.15	47.45
GB7	APR	77.89	63.19
GB8	MAY	88.34	73.64
GB9	JUNE	92.53	77.95
GB10	JULY	92.24	77.78
GB11	AUG	80.21	75.65
GB12	SEPT	78.29	73.73
HCAP		207.23	207.23
HB1	OCT	79.52	82.28
HB2	NOV	83.41	86.18
HB3	DEC	87.29	90.06
HB4	JAN	73.37	73.37
HB5	FEB	76.14	76.14
HB6	MAR	60.44	60.44
HB7	APR	70.26	67.30
HB8	MAY	87.02	84.05
HB9	JUNE	96.77	93.81
HB10	JULY	86.15	99.91
HB11	AUG	83.06	104.13
HB12	SEPT	76.45	108.38

TABLE 4- 7

DESIGN EVALUATIONS FOR SET 2

DEMAND	WQCP	FAILURE RATE		TEST	
SET		AVERAGE	STD.DEV.	STATISTIC	SATISFACTORY
V898	COVINGTON	0.01154	0.00355	9.28989	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01062	0.00341	8.47081	NO
	LYNCHBURG	0.00642	0.00254	3.95920	NO

Design Set 3

To allow feasible designs to be found for the years 2000 and 2020, the Lynchburg water quality constraint failure rate was raised to 6.9%, and the non-negative release constraints failure rates were raised to 6.6%.

With these changes, the six feasible designs given in Table 4-8 resulted. U095, with the highest demands of the designs feasible in set 1, did not produce a feasible design. The only feasible designs for the years 2000 and 2020 were based upon the EPA projections with 98% BOD_5 removal. The lowest BOD_5 removal rate in a feasible design was 95% for the year 1980. With one exception U895, the Hipes storages were constant for all designs in the projection period. The Gathright storages varied, but not enough to warrant consideration of staged construction.

The evaluation of these designs, given in Table 4-9, showed that a satisfactory design could not be found for Covington and that Lynchburg did not have a satisfactory design for the year 2020.

Design Set 4

For this run, the Lynchburg water quality constraint monthly failure rate was lowered to 2.5% and all other conditions remained the same. Table 4-10 lists the six feasible designs found for this run. They are for the same demand sets found feasible in design set 3.

Evaluation of these designs, shown in Table 4-11, indicated that satisfactory designs exist for Lynchburg for all years in the projection period, but that no satisfactory designs exist for Covington.

TABLE 4 - 8
LINEAR DECISION RULE DESIGNS FOR SET 3

DESIGN VARIABLE	MONTH	DEMAND SETS U298	U098	U898	U895	V898	V895
GCAP		279.05	279.05	276.89	282.22	230.98	230.98
GB1	OCT	92.43	92.43	91.76	93.41	69.23	69.23
GB2	NOV	86.80	86.80	86.13	87.79	67.32	67.32
GB3	DEC	81.47	81.47	80.80	82.45	65.53	65.53
GB4	JAN	77.40	77.40	76.73	78.38	65.00	65.00
GB5	FEB	77.94	77.94	75.78	81.11	70.94	70.94
GB6	MAR	89.43	89.43	87.26	92.59	41.35	41.35
GB7	APR	113.25	113.25	111.09	116.42	69.77	69.77
GB8	MAY	122.82	122.82	120.96	126.29	84.38	84.38
GB9	JUNE	121.37	121.37	119.80	125.13	88.69	88.57
GB10	JULY	115.25	115.25	113.98	115.64	88.52	81.81
GB11	AUG	107.18	107.18	106.21	107.86	86.39	79.57
GB12	SEPT	100.09	100.09	99.12	100.77	84.47	71.84
HCAP		207.23	207.23	207.23	216.41	207.23	207.23
HB1	OCT	76.29	97.77	82.89	81.92	100.30	90.15
HB2	NOV	75.78	100.21	85.33	84.36	100.21	92.58
HB3	DEC	75.20	75.20	75.20	78.69	75.20	75.20
HB4	JAN	73.37	78.49	73.37	76.86	78.49	78.49
HB5	FEB	76.14	76.14	68.67	72.16	76.14	76.14
HB6	MAR	60.44	60.44	60.44	63.93	60.44	60.44
HB7	APR	70.26	70.26	67.30	79.45	70.26	70.26
HB8	MAY	70.81	81.52	78.56	90.70	81.52	81.52
HB9	JUNE	75.35	88.98	86.02	98.16	88.98	88.98
HB10	JULY	77.89	93.48	76.07	95.07	93.48	92.76
HB11	AUG	76.31	96.11	78.70	84.18	96.11	85.95
HB12	SEPT	78.46	98.31	80.91	79.94	98.31	88.16

TABLE 4- 9

DESIGN EVALUATIONS FOR SET 3

DEMAND	WQCP	FAILURE RATE		TEST	
SET		AVERAGE	STD.DEV.	STATISTIC	SATISFACTORY
U298	COVINGTON	0.02279	0.00680	12.23997	NO
	LYNCHBURG	0.01137	0.00268	12.02180	NO
U098	COVINGTON	0.02279	0.00680	12.23997	NO
	LYNCHBURG	0.00075	0.00060	-25.55565	YES
U898	COVINGTON	0.02233	0.00709	11.45739	NO
	LYNCHBURG	0.0	0.0	************	YES
U895	COVINGTON	0.02242	0.00676	12.07365	NO
	LYNCHBURG	0.01558	0.00380	13.44706	NO
V898	COVINGTON	0.01446	0.00502	9.17170	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01133	0.00382	8.39010	NO
	LYNCHBURG	0.01325	0.00281	14.45854	NO

TABLE 4 -10
LINEAR DECISION RULE DESIGNS FOR SET 4

DESIGN		DEMAND SETS					
VARIABLE	MONTH	U298	U098	U898	U895	V898	V895
GCAP		281.04	279.05	276.89	282.22	230.98	238.66
GB1	OCT	93.05	92.43	91.76	93.41	69.23	71.61
GB2	NOV	87.42	86.80	86.13	87.79	67.32	69.71
GB3	DEC	82.09	81.47	80.80	82.45	65.53	67.92
GB4	JAN	78.01	77.40	76.73	78.38	65.00	67.39
GB5	FEB	79.93	77.94	75.78	81.11	70.94	73.32
GB6	MAR	91.41	89.43	87.26	92.59	41.35	49.04
GB7	APR	115.24	113.25	111.09	116.42	69.77	77.46
GB8	MAY	124.81	122.82	120.96	126.29	84.38	92.07
GB9	JUNE	123.36	121.37	119.80	125.13	88.69	96.26
GB10	JULY	117.24	115.25	113.98	115.64	88.52	95.97
GB11	AUG	108.80	107.18	106.21	107.86	86.39	82.90
GB12	SEPT	100.70	100.09	99.12	100.77	84.47	74.22
HCAP		207.23	207.23	207.23	243.86	207.23	207.23
HB1	OCT	76.29	76.29	97.33	92.35	100.30	78.43
HB2	NOV	75.78	75.78	75.78	89.70	75.78	75.78
HB3	DEC	75.20	75.20	75.20	89.12	78.56	78.56
HB4	JAN	73.37	73.37	73.37	87.29	73.37	73.37
HB5	FEB	76.14	68.67	68.67	82.59	76.14	76.14
HB6	MAR	60.44	60.44	60.44	88.78	60.44	60.44
HB7	APR	70.26	70.26	67.30	106.89	70.26	70.26
HB8	MAY	81.52	81.52	78.56	118.15	81.52	81.52
HB9	JUNE	88.98	88.98	86.02	125.61	88.98	88.98
HB10	JULY	83.59	93.48	90.51	114.58	93.48	78.36
HB11	AUG	76.31	96.11	93.14	97.62	96.11	76.31
HB12	SEPT	76.45	98.31	95.35	90.37	98.31	76.45

TABLE 4-11

DESIGN EVALUATIONS FOR SET 4

DEMAND SET	WQCP	FAILURE RATE AVERAGE	STD.DEV.	TEST STATISTIC	SATISFACTORY
U298	COVINGTON	0.02121	0.00661	11.52026	NO
	LYNCHBURG	0.00437	0.00135	0.67987	YES
U098	COVINGTON	0.02279	0.00680	12.23997	NO
	LYNCHBURG	0.00075	0.00060	-25.55565	YES
U898	COVINGTON	0.02233	0.00709	11.45739	NO
	LYNCHBURG	0.0	0.0	************	YES
U895	COVINGTON	0.02242	0.00676	12.07365	NO
	LYNCHBURG	0.00696	0.00239	5.21302	NO
V898	COVINGTON	0.01446	0.00502	9.17170	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01133	0.00346	9.26925	NO
	LYNCHBURG	0.00579	0.00236	3.06732	NO

The monthly failure rates of 2.5% for the water supply constraints were the most restrictive allowed by the forty-two to forty-five years of streamflow records available. Rather than stopping the search for feasible designs at this point, other modifications to the constraints were made:

a. The size of the flood control pools in the reservoirs was varied over the year, to make more storage available for water quality storage in the drier months, when demands are high and the probability of floods is lower.

b. For months with low probability of water quality failure, the allowable failure frequency was raised to 50%. The intent of this was to increase the surplus of dependable water over demands and thereby allow more generous release rules to result in the drier months.

c. The water quality constraints in certain high failure months were modified to allow no failures.

Design Set 5

In this set, the flood pool volumes for the two reservoirs were allowed to vary over the year. December through March flood control pools were left at the values assigned by the Corps of Engineers, and the remaining months' flood control pools were varied from 20 to 60 thousand acre-feet in 20 thousand acre-feet increments.

Table 4-12 lists the designs from the linear decision rule for these conditions. The same six designs that were feasible for set 4 are feasible for set 5.

TABLE 4 -12
LINEAR DECISION RULE DESIGNS FOR SET 5

DESIGN		DEMAND SETS					
VARIABLE	MONTH	U298	U098	U898	U895	V898	V895
GCAP		279.05	279.05	276.89	282.22	230.98	230.98
GB1	OCT	92.43	92.43	91.76	93.41	69.23	69.23
GB2	NOV	86.80	86.80	86.13	87.79	67.32	67.32
GB3	DEC	81.47	81.47	80.80	82.45	65.53	65.53
GB4	JAN	77.40	77.40	76.73	78.38	65.00	65.00
GB5	FEB	77.94	77.94	75.78	81.11	70.94	70.94
GB6	MAR	89.43	89.43	87.26	92.59	41.35	41.35
GB7	APR	113.25	113.25	111.09	116.42	69.77	69.77
GB8	MAY	122.82	122.82	120.96	126.29	84.38	84.38
GB9	JUNE	121.37	121.37	119.80	125.13	88.69	88.57
GB10	JULY	115.25	115.25	113.98	115.64	88.52	88.28
GB11	AUG	107.18	107.18	106.21	107.86	86.39	73.76
GB12	SEPT	100.09	100.09	99.12	100.77	84.47	71.84
HCAP		207.23	207.23	207.23	230.49	207.23	207.23
HB1	OCT	76.29	76.29	82.89	87.27	108.59	81.42
HB2	NOV	75.78	75.78	75.78	84.62	75.78	75.78
HB3	DEC	75.20	75.20	75.20	84.04	76.32	76.32
HB4	JAN	73.37	73.37	73.37	82.21	79.61	79.61
HB5	FEB	76.14	68.67	68.67	77.51	68.67	68.67
HB6	MAR	60.44	60.44	60.44	83.70	60.44	60.44
HB7	APR	78.55	78.55	78.55	101.81	78.55	78.55
HB8	MAY	82.90	89.81	89.81	113.07	89.81	89.81
HB9	JUNE	90.36	97.27	97.27	120.53	97.27	97.27
HB10	JULY	84.96	101.77	76.07	109.50	101.77	86.65
HB11	AUG	77.31	104.40	78.70	92.54	104.40	86.05
HB12	SEPT	76.45	106.60	80.91	85.29	106.60	79.43

Table 4-13 gives the evaluation results. Once again, no satisfactory design for Covington was found, and satisfactory designs for demands requiring 98% BOD_5 removal were found in all years for Lynchburg. In fact, the results were identical to the results for design set 4 except for U298 and V895. In these, the designs from set 4 had slightly lower failure rates.

Design Set 6

For this run, the water quality constraints for Covington in February and March and for Lynchburg from December to April were modified to allow 50% probability of failure. The resulting designs, shown in Table 4-14, were very similar to the designs in set 5. Table 4-15, the evaluation results for this run, shows that no designs satisfactory for Covington were found, and that only the Lynchburg designs with 98% BOD_5 removal were satisfactory for Lynchburg.

Design Set 7

For the next attempt to find a satisfactory design for Covington, the two months with the highest observed water quality failure rates for Covington were determined and their water quality constraints were modified to allow no failures. These were the months of November with a failure rate of .046 and June with a failure rate of .07.

The designs for this set are given in Table 4-16. Only the V898 and V895 demands produced feasible designs. According to the IBM Mathematical Programming System used to solve the linear programming problems, the four demands for which feasible designs had been found in the other runs, U298, U098, U898, and U895, were all infeasible

TABLE 4-13

DESIGN EVALUATIONS FOR SET 5

DEMAND SET	WQCP	FAILURE RATE AVERAGE	STD.DEV.	TEST STATISTIC	SATISFACTORY
U295	COVINGTON	0.02279	0.00680	12.23997	NO
	LYNCHBURG	0.00462	0.00119	1.70539	YES
U098	COVINGTON	0.02279	0.00680	12.23997	NO
	LYNCHBURG	0.00075	0.00060	-25.55565	YES
U898	COVINGTON	0.02233	0.00709	11.45739	NO
	LYNCHBURG	0.0	0.0	************	YES
U895	COVINGTON	0.02242	0.00676	12.07365	NO
	LYNCHBURG	0.00696	0.00239	5.21302	NO
V898	COVINGTON	0.01446	0.00502	9.17170	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01262	0.00399	9.46602	NO
	LYNCHBURG	0.00621	0.00240	3.80598	NO

TABLE 4 -14
LINEAR DECISION RULE DESIGNS FOR SET 6

DESIGN		DEMAND SETS					
VARIABLE	MONTH	U298	U098	U898	U895	V898	V895
GCAP		279.05	279.05	276.89	293.12	230.98	230.98
GB1	OCT	92.43	92.43	91.76	96.80	81.86	69.23
GB2	NOV	86.80	86.80	86.13	91.17	79.95	67.32
GB3	DEC	81.47	81.47	80.80	85.83	78.16	65.53
GB4	JAN	77.40	77.40	76.73	81.76	77.63	65.00
GB5	FEB	76.31	76.31	74.15	90.38	57.15	57.15
GB6	MAR	89.43	89.43	87.26	103.50	41.35	41.35
GB7	APR	113.25	113.25	111.09	127.33	69.77	69.77
GB8	MAY	122.82	122.82	120.96	137.19	84.38	84.38
GB9	JUNE	121.37	121.37	119.80	136.03	88.69	88.57
GB10	JULY	115.25	115.25	113.98	119.02	88.52	88.28
GB11	AUG	107.18	107.18	106.21	111.24	86.39	82.58
GB12	SEPT	100.09	100.09	99.12	104.15	84.47	71.84
HCAP		207.23	207.23	207.23	218.35	207.23	207.23
HB1	OCT	76.29	76.29	108.59	82.66	108.59	81.42
HB2	NOV	75.78	75.78	75.78	80.00	75.78	75.78
HB3	DEC	75.21	75.21	75.21	79.43	75.21	75.21
HB4	JAN	73.37	73.37	73.37	77.60	73.37	73.37
HB5	FEB	76.14	68.67	68.67	72.90	68.67	68.67
HB6	MAR	60.44	60.44	60.44	71.56	60.44	60.44
HB7	APR	78.56	78.56	78.56	89.67	78.56	78.56
HB8	MAY	82.90	89.81	89.81	100.93	89.81	89.81
HB9	JUNE	90.36	97.27	97.27	108.39	97.27	97.27
HB10	JULY	84.96	101.77	101.77	104.89	101.77	86.65
HB11	AUG	77.31	104.40	104.40	87.93	104.40	77.23
HB12	SEPT	76.45	106.61	106.61	80.67	106.61	79.43

TABLE 4-15

DESIGN EVALUATIONS FOR SET 6

DEMAND SET	WQCP	FAILURE RATE AVERAGE	STD.DEV.	TEST STATISTIC	SATISFACTORY
U298	COVINGTON	0.02304	0.00688	12.25997	NO
	LYNCHBURG	0.00462	0.00119	1.70539	YES
U098	COVINGTON	0.02304	0.00688	12.25997	NO
	LYNCHBURG	0.00079	0.00063	-23.88190	YES
U898	COVINGTON	0.02287	0.00724	11.55890	NO
	LYNCHBURG	0.0	0.0	************	YES
U895	COVINGTON	0.02342	0.00618	13.92208	NO
	LYNCHBURG	0.00708	0.00233	5.58302	NO
V898	COVINGTON	0.01525	0.00528	9.38812	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01158	0.00380	8.71610	NO
	LYNCHBURG	0.00550	0.00232	2.56779	NO

TABLE 4 -16
LINEAR DECISION RULE DESIGNS FOR SET 7

DESIGN VARIABLE	MONTH	DEMAND SETS	
		V898	V895
GCAP		251.13	265.11
GB1	OCT	75.48	79.81
GB2	NOV	73.57	77.90
GB3	DEC	71.78	76.11
GB4	JAN	71.25	75.58
GB5	FEB	79.87	84.20
GB6	MAR	61.51	75.48
GB7	APR	89.93	103.90
GB8	MAY	82.66	96.64
GB9	JUNE	86.96	100.82
GB10	JULY	86.79	91.25
GB11	AUG	84.67	89.00
GB12	SEPT	82.75	87.08
HCAP		207.23	207.23
HB1	OCT	78.43	78.43
HB2	NOV	75.78	75.78
HB3	DEC	75.21	75.21
HB4	JAN	73.37	73.37
HB5	FEB	76.14	76.14
HB6	MAR	60.44	60.44
HB7	APR	78.56	78.56
HB8	MAY	89.81	89.81
HB9	JUNE	97.27	97.27
HB10	JULY	101.77	95.94
HB11	AUG	76.31	83.06
HB12	SEPT	76.45	76.45

because of the non-negative release constraint for Gathright in March.

The evaluation given in Table 4-17 showed that both designs were satisfactory for Lynchburg, but not for Covington.

Design Set 8

For this set, the Gathright non-negative release constraint for March had its failure rate increased to 35%. Table 4-18 gives the results of this design search. There were six feasible designs produced, the same six as in sets 3, 4, 5, and 6. The evaluation results in Table 4-19 show that there are no designs satisfactory for Covington, and all designs except U895 were satisfactory for Lynchburg.

It was also noted that the observed failure frequencies were not appreciably different from those in design set 4, 5, or 6. The effect of relaxing the March non-negative constraint for Gathright was to increase the frequency of negative releases for March and April to values as high as .482. When these negative releases are prescribed by the rule, the reservoir contents should increase for the "optimal" release pattern to continue. Because the actual release is a small positive amount, the optimal pattern cannot hold, and the likelihood of sufficient water being available to satisfy all demands for the following summer is low. The effect of changing only a few monthly failure frequencies to zero was seen to be neglible in going from design set 5 to 6. For these reasons it was felt that further efforts to adjust the constraints would be non-productive, and the search for a design which would satisfy the Covington demands was terminated.

TABLE 4-17

DESIGN EVALUATIONS FOR SET 7

DEMAND SET	WQCP	FAILURE RATE AVERAGE	FAILURE RATE STD.DEV.	TEST STATISTIC	SATISFACTORY
V898	COVINGTON	0.01083	0.00309	9.62968	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01012	0.00283	9.42775	NO
	LYNCHBURG	0.00471	0.00130	1.84571	YES

TABLE 4 -18
LINEAR DECISION RULE DESIGNS FOR SET 8

DESIGN VARIABLE	MONTH	DEMAND SETS U298	U098	U898	U895	V898	V895
GCAP		317.51	317.51	315.35	332.08	251.13	265.11
GB1	OCT	104.36	104.36	103.69	108.87	75.48	79.81
GB2	NOV	98.73	98.73	98.06	103.24	73.57	77.90
GB3	DEC	93.39	93.39	92.72	97.91	71.78	76.11
GB4	JAN	89.32	89.32	88.65	93.84	71.25	75.58
GB5	FEB	97.94	87.89	85.72	102.46	63.40	67.74
GB6	MAR	127.89	127.89	125.72	142.46	61.51	75.48
GB7	APR	151.71	151.71	149.55	166.28	89.93	103.90
GB8	MAY	139.40	139.40	137.54	154.27	82.66	96.64
GB9	JUNE	137.95	137.95	136.38	153.11	86.96	100.82
GB10	JULY	131.83	131.83	130.56	135.75	86.79	91.25
GB11	AUG	123.76	123.76	122.79	127.98	84.67	89.00
GB12	SEPT	116.67	116.67	115.70	120.89	82.75	87.08
HCAP		207.23	207.23	207.23	217.79	207.23	207.23
HB1	OCT	78.43	108.59	108.59	82.45	108.59	78.43
HB2	NOV	75.78	75.78	75.78	79.79	75.78	75.78
HB3	DEC	75.21	75.21	75.21	79.22	75.21	75.21
HB4	JAN	73.37	73.37	73.37	77.39	73.37	73.37
HB5	FEB	76.14	68.67	68.67	72.69	68.67	68.67
HB6	MAR	60.44	60.44	60.44	71.01	60.44	60.44
HB7	APR	78.56	78.56	78.56	89.12	78.56	78.56
HB8	MAY	82.90	89.81	89.81	100.38	89.81	89.81
HB9	JUNE	90.36	97.27	97.27	107.84	97.27	97.27
HB10	JULY	84.96	101.77	101.77	104.68	101.77	95.94
HB11	AUG	77.31	104.40	104.40	87.72	104.40	83.06
HB12	SEPT	76.45	106.61	106.61	80.46	106.61	76.45

TABLE 4-19

DESIGN EVALUATIONS FOR SET 8

DEMAND SET	WQCP	FAILURE RATE AVERAGE	FAILURE RATE STD.DEV.	TEST STATISTIC	SATISFACTORY
U298	COVINGTON	0.02158	0.00627	12.41911	NO
	LYNCHBURG	0.00442	0.00127	0.86789	YES
U098	COVINGTON	0.02442	0.00706	12.83235	NO
	LYNCHBURG	0.00096	0.00068	-21.20711	YES
U898	COVINGTON	0.02429	0.00721	12.47967	NO
	LYNCHBURG	0.0	0.0	************	YES
U895	COVINGTON	0.02400	0.00599	14.80868	NO
	LYNCHBURG	0.00579	0.00170	4.26731	NO
V898	COVINGTON	0.01067	0.00342	8.50609	NO
	LYNCHBURG	0.0	0.0	************	YES
V895	COVINGTON	0.01004	0.00314	8.37523	NO
	LYNCHBURG	0.00483	0.00137	2.16854	YES

The best designs for each WQCP are summarized in Table 4-20. It is interesting to note that design set 4 produced the best overall results.

The failure to find a design satisfactory for Covington prompted a comparison of the total demand at Covington and the total flow past Covington. It was found that the average yearly surplus of flow over demands at Covington varied from a low of 298 thousand acre-feet to a high of 366 thousand acre-feet. This is approximately 36.5 cubic feet per second over the demands on a daily basis, or 2895 cubic feet per second of the average monthly flow. This is approximately 16% of the mean monthly Covington flow of about 18000 cubic feet per second. A truly satisfactory method of reservoir design should produce designs capable of making better use of the excess. If the excess were from spills, i.e., releases when Gathright reservoir was full, they would be understandable. However, the maximum frequency of spills for Gathright in any evaluation run was .00137, approximately one month in each sixty years. Unless the spills were of "Biblical" scale, they could not have accounted for the observed excess of flow over demand.

Discussion of results

There are significant differences in size between the reservoirs in the Corps of Engineers' designs and the designs determined in this study. The Corps' design storages for Hipes and Gathright, given in Table 3-2, are 304 and 203 thousand acre-feet respectively. The design storages determined in this study are 207 thousand acre-feet for Hipes and range from 230 to 280 thousand acre-feet for Gathright. A

TABLE 4-20

SUMMARY OF "BEST" RESULTS FOR ALL DESIGN SETS

COVINGTON

YEAR	WATER QUALITY FAILURE RATE	DEMAND SET	DESIGN SET
2020	0.02121	U298	4
2000	0.02279	U098	4
1980	0.01004	V895	8

LYNCHBURG

YEAR	WATER QUALITY FAILURE RATE	DEMAND SET	DESIGN SET
2020	0.00437	U298	4
2000	0.00075	U098	4,5
1980	0.0	U898, V898	1,2,3,4, 5,6,7,8

major part of the difference in the Gathright storages stems from the assumption used with the linear decision rule that the dam is located at the streamflow gauge site. If the storages determined for the Gathright reservoir are reduced by the ratio of the drainage area above the streamflow gauge to the drainage area above the streamflow gauge to the drainage area above the actual location of the dam, the range of storages is reduced to 193 to 235 thousand acre-feet. This range includes the Corps of Engineers' design storage for the reservoir, indicating that the linear decision rule design is more conservative than the Corps' design. Because the Corps requires the demands to be met, their design procedure causes the reservoir to store more water in wet months than would a reservoir operated strictly by a linear decision rule.

The inflexibility of the linear decision rule operations can be understood by examining the water quality constraints, equations 5C and 5L. They constrain the system to supply enough water to meet the demands as long as the flows stay above a minimum level corresponding with the allowable monthly failure rate. If the flows fall below this level the constraint will likely be violated, but if the flows are above this value, the model dictates the same release no matter what the surplus flow is.

This suggests that the primary use of the linear decision rule design should be to determine initial storage estimates, with the detailed operating rules being determined by other methods in later design stages. These detailed rules would determine the amounts of excess water over demands to be released and stored in each month with a surplus. The model used should also be capable of deciding whether to meet demands in one dry month, at the expense of a catastrophic failure in the next month, or accept relatively small failures in both months. Two months with the D.O. level dropping to 4.5 mg/l are preferable to one month above the standard, 5.0 mg/l, and the next month with the D.O. level at or very near zero. However, the standards are set up without differentiation between "large" and "small" failures.

The storage prescribed by the linear decision rule for the Hipes reservoir is only two-thirds that of the Corps' design, 207 versus 304 thousand acre-feet. Even so, designs were found that were satisfactory for Lynchburg, A possible explanation for this is that the Corps of Engineers design took into account the demands of the Richmond area, which were not included in this study.

In the later years of the projection period, the only designs satisfactory for Lynchburg, and the "best" designs for Covington, were those with 98% removal. If better than 98% removal were in effect above Covington, the standards might be able to be met. A choice must then be made between additional treatment costs and the cost of the dam. The linear decision rule shows that 98% and higher treatment levels will be required, so the effect of constructing dams will be to keep the extra costs of treatment as low as possible.

The evaluation of the designs was also affected by the performance of the streamflow generation model. The failure of the generating technique to match 34 of the 48 skewnesses of the historic flows probably contributed to unsatisfactory evaluations of some designs.

Tables A2-6 to A2-9 in Appendix 2 show that in almost all of the skewness failures the synthetic skewness values were greater than the historic skewness values. This indicates that the proportion of monthly flows less than the mean monthly flow is greater in the synthetic flows than in the historic flows. This, in turn, can lead to more months with water quality standard failures than would be expected if the generator perfectly duplicated the skewnesses of the historic flows.

An unexpected problem with the linear decision rule model was the need to relax the non-negative release constraints to obtain feasible solutions to the linear program. These constraints, not apparently needed in the probabilistic formulation, become necessary as a lower bound on the releases in the deterministic problem. Unfortunately, they not only place a lower bound on the releases, but they also limit the demands that can be met. This is clearly seen by comparing design sets 2 and 4. Two designs were feasible in set 2, with non-negative release and water quality failure rates of 2.5%. Six designs were feasible in set 4, and the only difference from set 2 was that the non-negative release failure rates were raised to 6.6%. Examination of Table 4-4 shows that from set 2 to set 4, the maximum demands that could be met at Covington and Lynchburg increased from 123 cfs and 710 cfs in set 2 to 220 cfs and 870 cfs in set 4.

V. SUMMARY AND CONCLUSIONS

A probabilistic linear programming model for finding the optimal storage and operating rules for a single reservoir was extended to the case of two reservoirs operating in series. This extended model was then used to find preliminary designs for the Gathright and Hipes multi-purpose reservoirs. The purposes of water quality maintenance, recreation, and flood control were considered in the design process. Flood flows were specified below each reservoir. Flood buffer pool levels were established, and minimum pool levels for recreation and esthetic values were defined. Projections of waste loads in the upper James River basin for the years 1980, 2000, and 2020 were made by the Environmental Protection Agency and the Virginia Division of Water Resources. These projections were used by the EPA to determine the flows necessary to maintain minimum dissolved oxygen levels at Lynchburg and Covington.

The linear programming model used required an allowed monthly failure frequency for demands placed on the system, while the allowed water quality failure rate was specified over a period of months, not for each month. Therefore a search for monthly water quality requirement failure rates which would yield the allowed overall rate was made. Candidate designs produced by the linear programming model were evaluated by simulation using synthetic streamflow.

Synthetic streamflows were generated using the Young-Pisano model with a modification based upon an Army Corps of Engineers model.

Conclusions

For the allowed water quality failure rate of one month in two hundred and forty (twenty years) to be met at Lynchburg, 98% BOD_5 removal for all waste discharges will be necessary by the year 1980. This is with both reservoirs in operation. At Covington, in the upper part of the basin, the overall water quality failure rate cannot be met in 1980 or later. This is in spite of the Gathright reservoir being in operation and 98% removal of BOD_5. Therefore, higher treatment level will be required in the upper basin.

Because of the conservative nature of the designs produced in this study, the linear decision rule model is not particularly useful for making final design decisions. However, it is very useful for limiting the number of designs to be evaluated by more precise models.

From the results shown, the design which should be used as the starting point for further design efforts in the upper James River Basin is the U298 design in set 4. All of the designs based upon 98% BOD_5 removal had identical storages for the Hipes reservoir, 207 thousand acre-feet, while storages for the Gathright reservoir varied from 230 to 280 thousand acre-feet. The primary differences between the designs were found in the release parameters.

The Young-Pisano synthetic streamflow generation model seemed to be sensitive to the differences in monthly correlations between flows. Further work to incorporate the monthly correlations instead of the average correlation over the year into the generation model would be useful. Research into the sensitivity of the model to differences in the drainage areas of streams being simulated is also warranted.

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APPENDIX I

TABLE A1- 1

EPA DAILY FLOW REQUIREMENTS FOR COVINGTON

YEAR	% BOD REMOVAL	OCT	NOV	DEC	JAN	FEB	MAR
1980	85	250.	190.	180.	180.	180.	185.
	90	205.	185.	180.	180.	180.	185.
	95	200.	185.	180.	180.	180.	185.
	98	200.	185.	180.	180.	180.	185.
2000	85	385.	230.	195.	185.	180.	225.
	90	265.	190.	180.	185.	180.	185.
	95	205.	185.	180.	180.	180.	185.
	98	205.	185.	180.	180.	180.	185.
2020	85	600.	360.	290.	270.	270.	330.
	90	430.	250.	210.	200.	200.	230.
	95	230.	190.	180.	180.	180.	190.
	98	205.	185.	180.	180.	180.	185.

YEAR	% BOD REMOVAL	APR	MAY	JUNE	JULY	AUG	SEPT
1980	85	240.	250.	365.	365.	365.	310.
	90	200.	205.	250.	250.	250.	220.
	95	200.	200.	215.	215.	215.	210.
	98	200.	200.	215.	215.	215.	210.
2000	85	360.	385.	555.	555.	555.	475.
	90	250.	265.	385.	385.	385.	325.
	95	200.	205.	225.	225.	225.	210.
	98	200.	205.	220.	220.	220.	210.
2020	85	553.	600.	910.	910.	910.	770.
	90	400.	430.	630.	630.	630.	540.
	95	216.	230.	330.	330.	330.	280.
	98	200.	205.	220.	220.	220.	210.

AFTER MCGEE, PERSONNAL COMMUNICATION (30)

TABLE A1- 2

EPA DAILY FLOW REQUIREMENTS FOR LYNCHBURG

YEAR	% BOD REMOVAL	OCT	NOV	DEC	JAN	FEB	MAR
1980							
	85	1470.	870.	700.	570.	640.	820.
	90	930.	580.	460.	380.	430.	540.
	95	500.	310.	250.	200.	240.	290.
	98	235.	212.	210.	200.	210.	210.
2000							
	85	2300.	1410.	1090.	900.	1020.	1320.
	90	1240.	760.	600.	500.	570.	720.
	95	650.	410.	330.	280.	310.	390.
	98	315.	240.	225.	225.	230.	240.
2020							
	85	3890.	2320.	1800.	1500.	1720.	2200.
	90	2280.	1330.	1060.	880.	980.	1280.
	95	890.	550.	450.	360.	420.	520.
	98	420.	270.	270.	225.	225.	240.

YEAR	% BOD REMOVAL	APR	MAY	JUNE	JULY	AUG	SEPT
1980							
	85	1360.	1590.	2730.	2730.	2730.	2180.
	90	880.	990.	1570.	1570.	1570.	1380.
	95	470.	530.	870.	870.	870.	680.
	98	230.	240.	290.	290.	290.	260.
2000							
	85	2170.	2480.	4260.	4260.	4260.	3400.
	90	1160.	1340.	2270.	2270.	2270.	1820.
	95	610.	690.	1100.	1100.	1100.	900.
	98	300.	330.	510.	510.	510.	420.
2020							
	85	3640.	4160.	8416.	8416.	8416.	6150.
	90	2120.	2420.	4200.	4200.	4200.	3360.
	95	850.	960.	1540.	1540.	1540.	1240.
	98	390.	420.	720.	720.	720.	570.

AFTER MCGEE, PERSONNAL COMMUNICATION (30)

TABLE A1- 3

VIRGINIA DAILY FLOW REQUIREMENTS FOR COVINGTON

YEAR	% BOD REMOVAL	OCT	NOV	DEC	JAN	FEB	MAR
1980							
	85	170.	123.	121.	121.	121.	121.
	90	124.	122.	121.	121.	121.	121.
	95	121.	121.	121.	121.	121.	121.
	98	121.	121.	121.	121.	121.	121.
2000							
	85	435.	253.	220.	210.	205.	243.
	90	290.	205.	205.	205.	205.	205.
	95	223.	205.	205.	205.	205.	205.
	98	223.	205.	205.	205.	205.	205.
2020							
	85	860.	545.	485.	470.	454.	521.
	90	630.	467.	460.	456.	454.	468.
	95	510.	467.	460.	456.	454.	468.
	98	510.	467.	460.	456.	454.	468.

YEAR	% BOD REMOVAL	APR	MAY	JUNE	JULY	AUG	SEPT
1980							
	85	161.	170.	263.	263.	263.	215.
	90	121.	124.	168.	168.	168.	145.
	95	121.	121.	123.	123.	123.	121.
	98	121.	121.	121.	121.	121.	121.
2000							
	85	403.	435.	620.	620.	620.	532.
	90	270.	290.	430.	430.	430.	360.
	95	221.	223.	260.	260.	260.	240.
	98	221.	223.	240.	204.	240.	240.
2020							
	85	799.	860.	1225.	1225.	1225.	1060.
	90	595.	630.	860.	860.	860.	750.
	95	504.	510.	552.	552.	552.	530.
	98	504.	510.	548.	548.	548.	530.

AFTER MCGEE, PERSONNAL COMMUNICATION (30)

TABLE A1- 4

VIRGINIA DAILY FLOW REQUIREMENTS FOR LYNCHBURG

YEAR	% BOD REMOVAL	OCT	NOV	DEC	JAN	FEB	MAR
1980							
	85	1180.	760.	600.	480.	560.	420.
	90	850.	490.	370.	310.	350.	460.
	95	420.	260.	200.	150.	190.	240.
	98	185.	150.	150.	150.	150.	150.
2000							
	85	3750.	1900.	1450.	1225.	1350.	1750.
	90	1975.	1175.	900.	750.	850.	1100.
	95	900.	500.	350.	300.	325.	450.
	98	350.	250.	250.	250.	250.	250.
2020							
	85	10800.	5100.	3600.	2800.	3300.	4600.
	90	5400.	2600.	1850.	1550.	1800.	2400.
	95	1950.	1100.	800.	700.	750.	900.
	98	600.	400.	400.	400.	400.	400.

YEAR	% BOD REMOVAL	APR	MAY	JUNE	JULY	AUG	SEPT
1980							
	85	1120.	1250.	2000.	2000.	2000.	1590.
	90	800.	900.	1350.	1350.	1350.	1150.
	95	400.	450.	710.	710.	710.	580.
	98	180.	190.	300.	300.	300.	240.
2000							
	85	3425.	4100.	8500.	8500.	8500.	6200.
	90	1850.	2125.	4050.	4050.	4050.	3000.
	95	850.	950.	1425.	1425.	1425.	1200.
	98	325.	375.	625.	625.	625.	475.
2020							
	85	10000.	11600.	26600.	26600.	26600.	18200.
	90	5000.	6000.	12700.	12700.	12700.	9200.
	95	1800.	2100.	3500.	3500.	3500.	2800.
	98	500.	600.	1100.	1100.	1100.	850.

AFTER MCGEE, PERSONNAL COMMUNICATION (30)

APPENDIX II

TABLE A2- 1 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS
AT STATION 1, TRANSFORMATIONS USED
WILSON-HILFERTY

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT		6344.5	5998.2	6252.9	6507.6
NOV		7943.9	7422.2	7804.8	8187.4
DEC		14354.	13834.	14421.	15008.
JAN		19197.	18655.	19592.	20530.
FEB		21667.	20739.	21550.	22361.
MAR		32688.	31537.	32477.	33417.
APR		23057.	22495.	22995.	23495.
MAY		17816.	17206.	17946.	18685.
JUNE		9282.4	8768.9	9255.3	9741.7
JULY		6632.9	6453.1	6789.4	7125.7
AUG		6467.9	6174.3	6548.6	6922.8
SEPT		4715.4	4296.0	4577.1	4858.2
VARIANCE					
OCT		0.33018E 08	0.27603E 08	0.32758E 08	0.37912E 08
NOV		0.39760E 08	0.29889E 08	0.36143E 08	0.42396E 08
DEC	*	0.11568E 09	0.90264E 08	0.10079E 09	0.11131E 09
JAN		0.14018E 09	0.12307E 09	0.14146E 09	0.15985E 09
FEB		0.10979E 09	0.90773E 08	0.10082E 09	0.11087E 09
MAR		0.23519E 09	0.19989E 09	0.22637E 09	0.25285E 09
APR		0.10521E 09	0.93174E 08	0.10377E 09	0.11437E 09
MAY		0.78847E 08	0.63720E 08	0.74870E 08	0.86019E 08
JUNE		0.47916E 08	0.31472E 08	0.42323E 08	0.53173E 08
JULY		0.21098E 08	0.17298E 08	0.21012E 08	0.24727E 08
AUG		0.38697E 08	0.29001E 08	0.38198E 08	0.47396E 08
SEPT		0.16694E 08	0.11445E 08	0.14747E 08	0.18048E 08
SKEWNESS					
OCT		2.5354	1.9992	2.4478	2.8963
NOV		1.4460	1.1292	1.3516	1.5740
DEC		0.96522	0.75012	0.90638	1.0626
JAN		1.1684	0.74886	0.95968	1.1705
FEB		0.15878	0.59619E-01	0.21689	0.37417
MAR		1.1375	0.82198	1.0471	1.2723
APR		0.52692	0.33559	0.52798	0.72038
MAY		0.84288	0.53034	0.86307	1.1958
JUNE	*	2.9547	2.0877	2.4703	2.8530
JULY	*	2.2849	1.5889	1.9010	2.2130
AUG	*	3.0289	2.0689	2.4099	2.7509
SEPT		3.6014	2.5881	3.0985	3.6090

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 2 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT STATION 2, TRANSFORMATIONS USED WILSON-HILFERTY

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT	*	1802.4	1579.4	1663.0	1746.6
NOV		2587.2	2373.4	2504.7	2636.0
DEC		4560.0	4268.7	4445.2	4621.8
JAN		7028.8	6470.9	6840.9	7211.0
FEB		8049.2	7689.8	7945.6	8201.5
MAR		12079.	11515.	11823.	12130.
APR		8002.6	7700.3	7879.5	8058.7
MAY		5747.9	5553.7	5779.0	6004.2
JUNE		2345.9	2136.9	2246.7	2356.6
JULY		1356.0	1272.6	1335.2	1397.8
AUG	*	1798.8	1500.4	1588.5	1676.5
SEPT	*	975.98	863.63	916.13	968.63
VARIANCE					
OCT	*	0.35352E 07	0.20330E 07	0.24791E 07	0.29253E 07
NOV	*	0.70975E 07	0.39692E 07	0.46794E 07	0.53897E 07
DEC	*	0.14431E 08	0.86964E 07	0.99997E 07	0.11303E 08
JAN	*	0.25948E 08	0.17217E 08	0.19552E 08	0.21886E 08
FEB	*	0.16906E 08	0.11332E 08	0.12357E 08	0.13381E 08
MAR	*	0.38669E 08	0.26318E 08	0.29654E 08	0.32989E 08
APR	*	0.19345E 08	0.13709E 08	0.15263E 08	0.16816E 08
MAY	*	0.13096E 08	0.86873E 07	0.99655E 07	0.11244E 08
JUNE	*	0.41091E 07	0.22615E 07	0.28216E 07	0.33818E 07
JULY	*	0.97003E 06	0.63023E 06	0.72455E 06	0.81888E 06
AUG	*	0.70771E 07	0.36938E 07	0.45361E 07	0.53784E 07
SEPT	*	0.64524E 06	0.38576E 06	0.45962E 06	0.53349E 06
SKEWNESS					
OCT		2.1847	1.3353	1.8634	2.3916
NOV	*	1.7697	1.2081	1.3960	1.5839
DEC		1.0328	0.70028	0.87131	1.0423
JAN	*	1.2685	0.82008	0.94659	1.0731
FEB		0.14969	0.33388E-01	0.19291	0.35244
MAR		0.79607	0.53165	0.78414	1.0366
APR		0.81686	0.58316	0.79802	1.0129
MAY		0.67822	0.47528	0.74078	1.0063
JUNE	*	2.1506	1.3660	1.7229	2.0798
JULY	*	1.8759	1.2265	1.4554	1.6843
AUG	*	3.1474	2.1195	2.5541	2.9888
SEPT		2.2973	1.6086	1.9647	2.3209

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 3 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS
AT STATION 3, TRANSFORMATIONS USED
WILSON-HILFERTY

STATISTIC NAME/ MONTH		HISTORIC VALUE		CONFIDENCE INTERVAL	
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT	*	5866.6	5045.7	5365.4	5685.1
NOV		7029.4	6544.3	6832.9	7121.5
DEC	*	10828.	9761.2	10239.	10718.
JAN		16116.	15015.	15888.	16760.
FEB		17577.	16932.	17407.	17882.
MAR		24047.	23241.	23820.	24400.
APR		18240.	17548.	18040.	18531.
MAY		12902.	12182.	12823.	13463.
JUNE		6206.0	5845.8	6127.4	6408.9
JULY	*	4422.3	3755.4	4043.6	4331.9
AUG	*	5204.7	4395.1	4653.4	4911.8
SEPT	*	3476.6	2984.9	3204.9	3424.8
VARIANCE					
OCT	*	0.44766E 08	0.26428E 08	0.32070E 08	0.37711E 08
NOV	*	0.44235E 08	0.26242E 08	0.29995E 08	0.33748E 08
DEC	*	0.85030E 08	0.51887E 08	0.60551E 08	0.69215E 08
JAN	*	0.13446E 09	0.90867E 08	0.10582E 09	0.12077E 09
FEB	*	0.65825E 08	0.43378E 08	0.47544E 08	0.51710E 08
MAR	*	0.13563E 09	0.90386E 08	0.10146E 09	0.11253E 09
APR	*	0.93113E 08	0.67011E 08	0.74125E 08	0.81240E 08
MAY	*	0.69867E 08	0.46760E 08	0.54460E 08	0.62160E 08
JUNE	*	0.25707E 08	0.16299E 08	0.19483E 08	0.22668E 08
JULY	*	0.38531E 08	0.20592E 08	0.24527E 08	0.28463E 08
AUG	*	0.49518E 08	0.25984E 08	0.32388E 08	0.38791E 08
SEPT	*	0.12527E 08	0.71309E 07	0.85304E 07	0.99300E 07
SKEWNESS					
OCT		2.4133	1.6276	2.1776	2.7276
NOV		1.2122	0.93893	1.0981	1.2573
DEC		1.6956	1.1752	1.4684	1.7617
JAN	*	1.2298	0.74239	0.91310	1.0838
FEB		-0.26947E-01	-0.95272E-01	0.65728E-01	0.22673
MAR		0.77923	0.47741	0.72451	0.97162
APR		0.64720	0.35581	0.52145	0.68710
MAY		1.1037	0.69744	1.0286	1.3597
JUNE	*	1.8296	1.1841	1.4803	1.7766
JULY	*	3.3389	1.9884	2.4553	2.9222
AUG	*	3.4745	2.2729	2.7289	3.1848
SEPT	*	2.3229	1.5398	1.8706	2.2014

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 4 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT STATION 4, TRANSFORMATIONS USED WILSON-HILFERTY

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT		58435.	53731.	56337.	58944.
NOV		64416.	59942.	62595.	65247.
DEC		0.10419E 06	96773.	0.10163E 06	0.10648E 06
JAN		0.14535E 06	0.13812E 06	0.14614E 06	0.15417E 06
FEB		0.16026E 06	0.15386E 06	0.15858E 06	0.16330E 06
MAR		0.22760E 06	0.21942E 06	0.22468E 06	0.22993E 06
APR		0.17181E 06	0.16730E 06	0.17099E 06	0.17468E 06
MAY		0.12347E 06	0.11956E 06	0.12471E 06	0.12986E 06
JUNE		70527.	68003.	70886.	73769.
JULY		46867.	45328.	47136.	48945.
AUG		60249.	55841.	59326.	62811.
SEPT		42077.	37801.	40588.	43375.
VARIANCE					
OCT		0.33047E 10	0.24640E 10	0.29298E 10	0.33956E 10
NOV	*	0.24803E 10	0.18120E 10	0.20780E 10	0.23440E 10
DEC	*	0.63783E 10	0.45408E 10	0.52678E 10	0.59948E 10
JAN		0.94416E 10	0.73817E 10	0.87619E 10	0.10142E 11
FEB	*	0.51934E 10	0.40550E 10	0.44669E 10	0.48788E 10
MAR	*	0.10979E 11	0.83862E 10	0.96281E 10	0.10870E 11
APR		0.68724E 10	0.57907E 10	0.63350E 10	0.68794E 10
MAY		0.37967E 10	0.30219E 10	0.34992E 10	0.39764E 10
JUNE	*	0.21754E 10	0.14559E 10	0.18110E 10	0.21661E 10
JULY		0.10589E 10	0.85850E 09	0.99224E 09	0.11260E 10
AUG		0.46926E 10	0.34057E 10	0.41225E 10	0.48393E 10
SEPT	*	0.13985E 10	0.91258E 09	0.11090E 10	0.13054E 10
SKEWNESS					
OCT		2.4976	1.9754	2.5195	3.0635
NOV	*	1.1730	0.83845	0.98920	1.1399
DEC		1.5026	1.0693	1.3100	1.5507
JAN	*	1.3247	0.85094	1.0563	1.2617
FEB		0.17614E-01	-0.66772E-01	0.10546	0.27769
MAR		0.82445	0.49987	0.77883	1.0578
APR		0.60374	0.36492	0.55867	0.75242
MAY		0.84292	0.60178	0.91676	1.2317
JUNE	*	2.2070	1.4994	1.7636	2.0278
JULY		2.4079	1.7723	2.2356	2.6989
AUG	*	2.5153	1.7006	2.0105	2.3205
SEPT	*	2.4045	1.6634	1.9654	2.2674

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 5 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT ALL STATIONS, TRANSFORMATIONS USED WILSON-HILFERTY

STATISTIC NAME/ STATIONS		HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
CROSS CORRELATION					
1 1		1.0000	1.0000	1.0000	1.0000
2 1	*	0.83641	0.78791	0.79866	0.80942
3 1	*	0.77186	0.74247	0.75510	0.76772
4 1	*	0.92597	0.88896	0.89419	0.89941
2 2		1.0000	1.0000	1.0000	1.0000
3 2	*	0.84952	0.84982	0.85563	0.86145
4 2	*	0.86351	0.83874	0.84523	0.85172
3 3		1.0000	1.0000	1.0000	1.0000
4 3	*	0.89932	0.86027	0.86762	0.87496
4 4		1.0000	1.0000	1.0000	1.0000
SERIAL CORRELATION					
1 1	*	0.30250	0.36924	0.38991	0.41059
2 1	*	0.27811	0.27911	0.29509	0.31108
3 1	*	0.27170	0.27361	0.29502	0.31643
4 1	*	0.28849	0.37538	0.39380	0.41221
1 2	*	0.24491	0.31194	0.33072	0.34950
2 2	*	0.29417	0.32142	0.33908	0.35674
3 2	*	0.26159	0.30441	0.32398	0.34355
4 2	*	0.24731	0.34700	0.36570	0.38440
1 3	*	0.25316	0.30379	0.32284	0.34190
2 3	*	0.27622	0.28662	0.30328	0.31994
3 3	*	0.30842	0.32734	0.34607	0.36481
4 3	*	0.27039	0.36335	0.38197	0.40059
1 4	*	0.32481	0.33726	0.35631	0.37536
2 4	*	0.32704	0.28116	0.29669	0.31221
3 4	*	0.34923	0.30659	0.32547	0.34434
4 4	*	0.34517	0.38558	0.40245	0.41931

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 6 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS
AT STATION 1, TRANSFORMATIONS USED
LOGARITHMIC

STATISTIC NAME/ MONTH		HISTCRIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT		6344.5	5815.7	6205.3	6594.9
NOV		7943.9	7345.4	7955.6	8565.7
DEC		14354.	14008.	15124.	16240.
JAN		19197.	18737.	19792.	20847.
FEB		21667.	21331.	22482.	23633.
MAR		32688.	31650.	32744.	33838.
APR		23057.	22605.	23213.	23820.
MAY		17816.	17462.	18095.	18729.
JUNE		9282.4	8849.7	9152.7	9455.7
JULY		6632.9	6208.5	6441.8	6675.1
AUG	*	6467.9	5758.3	6079.3	6400.3
SEPT	*	4715.4	4357.0	4483.8	4610.7
VARIANCE					
OCT	*	0.33018E 08	0.17138E 08	0.21461E 08	0.25784E 08
NOV		0.39760E 08	0.34031E 08	0.47551E 08	0.61071E 08
DEC	*	0.11568E 09	0.18057E 09	0.23939E 09	0.29821E 09
JAN	*	0.14018E 09	0.15703E 09	0.21253E 09	0.26803E 09
FEB	*	0.10979E 09	0.16830E 09	0.23662E 09	0.30493E 09
MAR		0.23519E 09	0.19534E 09	0.22649E 09	0.25765E 09
APR	*	0.10521E 09	0.10692E 09	0.12197E 09	0.13702E 09
MAY	*	0.78847E 08	0.84491E 08	0.99849E 08	0.11521E 09
JUNE	*	0.47916E 08	0.26097E 08	0.30817E 08	0.35537E 08
JULY	*	0.21098E 08	0.11164E 08	0.13604E 08	0.16044E 08
AUG	*	0.38697E 08	0.13745E 08	0.17427E 08	0.21109E 08
SEPT	*	0.16694E 08	0.56229E 07	0.65583E 07	0.74937E 07
SKEWNESS					
OCT	*	2.5354	1.6193	1.9620	2.3047
NOV	*	1.4460	1.8471	2.2765	2.7059
DEC	*	0.96522	2.4917	3.3461	4.2005
JAN	*	1.1684	1.4351	1.9361	2.4371
FEB	*	0.15878	1.4491	2.0116	2.5740
MAR		1.1375	0.94933	1.2086	1.4678
APR	*	0.52692	0.98348	1.4239	1.8642
MAY	*	0.84288	1.0884	1.4397	1.7909
JUNE	*	2.9547	1.2572	1.6976	2.1380
JULY	*	2.2849	1.1672	1.4822	1.7972
AUG	*	3.0289	1.5142	1.9491	2.3839
SEPT	*	3.6014	1.1552	1.3929	1.6307

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 7 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT STATION 2, TRANSFORMATIONS USED LOGARITHMIC

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT		1802.4	1615.3	1748.0	1880.7
NOV		2587.2	2402.5	2592.7	2782.9
DEC		4560.0	4321.3	4732.7	5144.1
JAN		7028.8	6855.2	7491.5	8127.8
FEB		8049.2	8031.9	8477.6	8923.1
MAR		12079.	11634.	12078.	12522.
APR		8002.6	7782.4	8119.1	8455.8
MAY		5747.9	5670.2	5966.2	6262.1
JUNE		2345.9	2192.9	2276.5	2360.1
JULY		1356.0	1250.5	1316.5	1382.5
AUG	*	1798.8	1434.8	1538.0	1641.2
SEPT	*	975.98	910.80	938.41	966.02
VARIANCE					
OCT	*	0.35352E 07	0.20040E 07	0.26709E 07	0.33378E 07
NOV		0.70975E 07	0.62494E 07	0.94385E 07	0.12628E 08
DEC	*	0.14431E 08	0.15173E 08	0.32636E 08	0.50098E 08
JAN	*	0.25948E 08	0.27331E 08	0.59079E 08	0.90828E 08
FEB	*	0.16906E 08	0.31932E 08	0.45599E 08	0.59267E 08
MAR	*	0.38669E 08	0.38809E 08	0.44724E 08	0.50640E 08
APR	*	0.19345E 08	0.20672E 08	0.25416E 08	0.30161E 08
MAY	*	0.13096E 08	0.16753E 08	0.22939E 08	0.29126E 08
JUNE	*	0.41091E 07	0.20694E 07	0.27776E 07	0.34857E 07
JULY	*	0.97003E 06	0.55242E 06	0.71914E 06	0.88585E 06
AUG	*	0.70771E 07	0.17374E 07	0.23579E 07	0.29784E 07
SEPT	*	0.64524E 06	0.33936E 06	0.39983E 06	0.46031E 06
SKEWNESS					
OCT		2.1847	1.9060	2.5712	3.2365
NOV	*	1.7697	2.3624	3.2173	4.0721
DEC	*	1.0328	2.5192	3.5382	4.5571
JAN	*	1.2685	1.7250	2.5884	3.4517
FEB	*	0.14969	1.4358	2.0593	2.6829
MAR	*	0.79607	1.1444	1.4356	1.7268
APR	*	0.81686	1.3683	1.7589	2.1494
MAY	*	0.67822	1.6129	2.2698	2.9267
JUNE		2.1506	1.4867	2.0978	2.7088
JULY		1.8759	1.2423	1.6711	2.0999
AUG		3.1474	2.1612	2.8496	3.5380
SEPT	*	2.2973	1.4817	1.8599	2.2380

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 8 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS
AT STATION 3, TRANSFORMATIONS USED
LOGARITHMIC

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT		5866.6	5337.6	5782.2	6226.8
NOV		7029.4	6856.3	7383.9	7911.4
DEC		10828.	10351.	11213.	12075.
JAN		16116.	15993.	17337.	18681.
FEB		17577.	17391.	18414.	19436.
MAR		24047.	23074.	24116.	25159.
APR		18240.	17816.	18507.	19199.
MAY		12902.	12549.	13263.	13977.
JUNE		6206.0	5861.6	6127.7	6393.7
JULY	*	4422.3	3546.8	3788.0	4029.2
AUG	*	5204.7	4347.7	4708.7	5069.7
SEPT	*	3476.6	3146.0	3290.4	3434.7
VARIANCE					
OCT		0.44766E 08	0.29886E 08	0.41113E 08	0.52340E 08
NOV	*	0.44235E 08	0.59291E 08	0.83656E 08	0.10802E 09
DEC	*	0.85030E 08	0.99646E 08	0.14519E 09	0.19074E 09
JAN	*	0.13446E 09	0.15744E 09	0.29809E 09	0.43875E 09
FEB	*	0.65825E 08	0.11993E 09	0.16384E 09	0.20775E 09
MAR	*	0.13563E 09	0.14073E 09	0.16375E 09	0.18677E 09
APR	*	0.93113E 08	0.10504E 09	0.13449E 09	0.16395E 09
MAY	*	0.69867E 08	0.75797E 08	0.95994E 08	0.11619E 09
JUNE	*	0.25707E 08	0.14612E 08	0.19343E 08	0.24074E 08
JULY	*	0.38531E 08	0.78709E 07	0.98886E 07	0.11906E 08
AUG	*	0.49518E 08	0.19551E 08	0.25787E 08	0.32023E 08
SEPT	*	0.12527E 08	0.60054E 07	0.78988E 07	0.97923E 07
SKEWNESS					
OCT		2.4133	2.2880	2.8277	3.3674
NOV	*	1.2122	2.5477	3.3638	4.1799
DEC	*	1.6956	2.2654	3.0169	3.7684
JAN	*	1.2298	1.8809	2.5211	3.1613
FEB	*	-0.26947E-01	1.3918	1.7994	2.2071
MAR	*	0.77923	1.1472	1.4297	1.7122
APR	*	0.64720	1.3957	1.8838	2.3718
MAY	*	1.1037	1.5491	2.0260	2.5029
JUNE		1.8296	1.4177	1.8375	2.2574
JULY	*	3.3389	1.8089	2.2383	2.6677
AUG		3.4745	2.0791	2.8154	3.5518
SEPT		2.3229	1.8027	2.2932	2.7838

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2- 9 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT STATION 4, TRANSFORMATIONS USED LOGARITHMIC

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT		58435.	53530.	57459.	61388.
NOV		64416.	61566.	65550.	69534.
DEC		0.10419E 06	99454.	0.10658E 06	0.11370E 06
JAN		0.14535E 06	0.13988E 06	0.15035E 06	0.16082E 06
FEB		0.16026E 06	0.15779E 06	0.16612E 06	0.17446E 06
MAR		0.22760E 06	0.21962E 06	0.22779E 06	0.23596E 06
APR		0.17181E 06	0.16807E 06	0.17312E 06	0.17817E 06
MAY		0.12347E 06	0.12065E 06	0.12538E 06	0.13010E 06
JUNE		70527.	67548.	69671.	71795.
JULY		46867.	43419.	45153.	46888.
AUG	*	60249.	52309.	55799.	59289.
SEPT	*	42077.	38958.	40341.	41723.
VARIANCE					
OCT	*	0.33047E 10	0.19432E 10	0.25835E 10	0.32238E 10
NOV	*	0.24803E 10	0.28187E 10	0.35499E 10	0.42811E 10
DEC	*	0.63783E 10	0.67406E 10	0.91993E 10	0.11658E 11
JAN		0.94416E 10	0.77511E 10	0.15676E 11	0.23601E 11
FEB	*	0.51934E 10	0.83136E 10	0.11453E 11	0.14593E 11
MAR		0.10979E 11	0.10256E 11	0.11784E 11	0.13311E 11
APR	*	0.68724E 10	0.71246E 10	0.86799E 10	0.10235E 11
MAY	*	0.37967E 10	0.39635E 10	0.47386E 10	0.55137E 10
JUNE	*	0.21754E 10	0.12801E 10	0.15311E 10	0.17821E 10
JULY	*	0.10589E 10	0.51727E 09	0.62277E 09	0.72826E 09
AUG	*	0.46926E 10	0.22779E 10	0.28707E 10	0.34635E 10
SEPT	*	0.13985E 10	0.71799E 09	0.86467E 09	0.10113E 10
SKEWNESS					
OCT		2.4976	1.7926	2.2948	2.7969
NOV	*	1.1730	2.1215	2.5813	3.0411
DEC	*	1.5026	2.0447	2.6835	3.3223
JAN	*	1.3247	1.5197	2.1954	2.8710
FEB	*	0.17614E-01	1.4751	1.9056	2.3361
MAR	*	0.82445	1.0226	1.2915	1.5603
APR	*	0.60374	1.1421	1.6505	2.1589
MAY	*	0.84292	1.0741	1.4434	1.8127
JUNE	*	2.2070	1.1736	1.4868	1.8000
JULY	*	2.4079	1.0591	1.3031	1.5470
AUG		2.5153	1.9880	2.7925	3.5971
SEPT	*	2.4045	1.4382	1.8144	2.1907

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2-10 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT ALL STATIONS, TRANSFORMATIONS USEC LOGARITHMIC

STATISTIC NAME/ STATIONS		HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
CROSS CORRELATION					
1 1		1.0000	1.0000	1.0000	1.0000
2 1		0.83641	0.83517	0.84296	0.85075
3 1	*	0.77186	0.78497	0.79533	0.80570
4 1	*	0.92597	0.90729	0.91234	0.91739
2 2		1.0000	1.0000	1.0000	1.0000
3 2	*	0.84952	0.84970	0.85919	0.86867
4 2		0.86351	0.86121	0.87078	0.88036
3 3		1.0000	1.0000	1.0000	1.0000
4 3	*	0.89932	0.90855	0.91373	0.91891
4 4		1.0000	1.0000	1.0000	1.0000
SERIAL CORRELATION					
1 1	*	0.30250	0.34566	0.37016	0.39466
2 1	*	0.27811	0.28144	0.30426	0.32708
3 1	*	0.27170	0.28074	0.30393	0.32712
4 1	*	0.28849	0.34829	0.37056	0.39283
1 2	*	0.24491	0.31804	0.34238	0.36673
2 2	*	0.29417	0.32982	0.35316	0.37650
3 2	*	0.26159	0.30057	0.32524	0.34992
4 2	*	0.24731	0.34482	0.36737	0.38991
1 3	*	0.25316	0.31006	0.33740	0.36474
2 3	*	0.27622	0.28721	0.31499	0.34277
3 3	*	0.30842	0.33838	0.36540	0.39242
4 3	*	0.27039	0.36628	0.39077	0.41526
1 4		0.32481	0.32243	0.34869	0.37494
2 4		0.32704	0.28565	0.31009	0.33453
3 4		0.34923	0.30781	0.33092	0.35404
4 4	*	0.34517	0.37088	0.39309	0.41530

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2-11 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS
AT STATION 1, TRANSFORMATIONS USED
LOGARITHMIC AND WILSON-HILFERTY

STATISTIC NAME/ MONTH	HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN				
OCT	6344.5	5909.2	6387.4	6865.5
NOV	7943.9	7406.4	7813.3	8220.2
DEC	14354.	13847.	14872.	15896.
JAN	19197.	18399.	19182.	19965.
FEB	21667.	20811.	21438.	22066.
MAR	32688.	32197.	33022.	33847.
APR	23057.	22846.	23593.	24340.
MAY	17816.	17405.	17962.	18519.
JUNE	9282.4	8691.1	9126.3	9561.4
JULY	6632.9	6372.4	6650.5	6928.7
AUG	6467.9	5886.1	6217.7	6549.4
SEPT	4715.4	4420.2	4685.4	4950.6
VARIANCE				
OCT	0.33018E 08	0.17621E 08	0.55786E 08	0.93951E 08
NOV	0.39760E 08	0.37999E 08	0.50931E 08	0.63862E 08
DEC *	0.11568E 09	0.13217E 09	0.18176E 09	0.23135E 09
JAN	0.14018E 09	0.11958E 09	0.14168E 09	0.16379E 09
FEB	0.10979E 09	0.99810E 08	0.10700E 09	0.11418E 09
MAR	0.23519E 09	0.19646E 09	0.23855E 09	0.28064E 09
APR	0.10521E 09	0.10321E 09	0.11871E 09	0.13422E 09
MAY	0.78847E 08	0.68495E 08	0.79035E 08	0.89576E 08
JUNE	0.47916E 08	0.27885E 08	0.43193E 08	0.58501E 08
JULY	0.21098E 08	0.15801E 08	0.23520E 08	0.31239E 08
AUG	0.38697E 08	0.22030E 08	0.34215E 08	0.46400E 08
SEPT	0.16694E 08	0.63837E 07	0.21672E 08	0.36959E 08
SKEWNESS				
OCT *	2.5354	2.6656	3.7623	4.8589
NOV *	1.4460	2.1426	2.7725	3.4024
DEC *	0.96522	1.6291	2.1887	2.7483
JAN	1.1684	0.91468	1.0876	1.2606
FEB *	0.15878	0.19277	0.31346	0.43415
MAR	1.1375	1.1124	1.5963	2.0802
APR *	0.52692	0.94189	1.1682	1.3946
MAY *	0.84288	0.85275	1.1592	1.4657
JUNE	2.9547	2.1248	2.6976	3.2704
JULY	2.2849	1.9495	2.5534	3.1572
AUG	3.0289	2.4687	3.4427	4.4168
SEPT	3.6014	2.8174	3.8826	4.9478

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2-12 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS
AT STATION 2, TRANSFORMATIONS USED
LOGARITHMIC AND WILSON-HILFERTY

STATISTIC NAME/ MONTH	HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN				
OCT	1802.4	1733.7	1877.2	2020.7
NOV	2587.2	2378.3	2600.1	2822.0
DEC	4560.0	4390.2	4675.6	4961.0
JAN	7028.8	6607.0	6953.3	7299.5
FEB	8049.2	7830.1	8058.8	8287.6
MAR	12079.	11902.	12260.	12619.
APR	8002.6	7891.7	8212.4	8533.1
MAY	5747.9	5627.1	5851.5	6076.0
JUNE	2345.9	2137.1	2268.1	2399.2
JULY	1356.0	1289.8	1350.8	1411.7
AUG	1798.8	1546.9	1780.5	2014.2
SEPT	975.98	924.07	971.79	1019.5
VARIANCE				
OCT	0.35352E 07	0.33283E 07	0.70834E 07	0.10838E 08
NOV	* 0.70975E 07	0.73735E 07	0.12813E 08	0.18253E 08
DEC	* 0.14431E 08	0.16028E 08	0.23281E 08	0.30533E 08
JAN	0.25948E 08	0.21140E 08	0.25541E 08	0.29941E 08
FEB	0.16906E 08	0.15717E 08	0.17195E 08	0.18672E 08
MAR	0.38669E 08	0.34218E 08	0.41326E 08	0.48435E 08
APR	0.19345E 08	0.18413E 08	0.21706E 08	0.24999E 08
MAY	0.13096E 08	0.13042E 08	0.15837E 08	0.18633E 08
JUNE	0.41091E 07	0.26128E 07	0.50624E 07	0.75120E 07
JULY	0.97003E 06	0.80632E 06	0.13049E 07	0.18035E 07
AUG	0.70771E 07	0.68718E 06	0.14016E 08	0.27345E 08
SEPT	0.64524E 06	0.42624E 06	0.88452E 06	0.13428E 07
SKEWNESS				
OCT	* 2.1847	3.2168	4.2069	5.1971
NOV	* 1.7697	2.7783	3.5938	4.4093
DEC	* 1.0328	1.6718	2.4572	3.2425
JAN	1.2685	1.0988	1.3004	1.5020
FEB	* 0.14969	0.15994	0.25316	0.34638
MAR	* 0.79607	1.0386	1.3470	1.6554
APR	* 0.81686	1.1017	1.3110	1.5204
MAY	* 0.67822	1.1127	1.6985	2.2843
JUNE	* 2.1506	2.6608	3.8192	4.9776
JULY	* 1.8759	2.3921	3.4087	4.4253
AUG	* 3.1474	3.7637	5.0401	6.3165
SEPT	* 2.2973	2.3071	3.3966	4.4862

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2-13 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT STATION 3, TRANSFORMATIONS USED LOGARITHMIC AND WILSON-HILFERTY

STATISTIC NAME/ MONTH		HISTORIC VALUE	CONFIDENCE INTERVAL		
			LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN					
OCT	*	5866.6	5878.3	6576.0	7273.6
NOV		7029.4	6711.9	7557.1	8402.3
DEC		10828.	10614.	11267.	11920.
JAN		16116.	15188.	16000.	16811.
FEB		17577.	17180.	17670.	18160.
MAR		24047.	23925.	24576.	25228.
APR		18240.	18050.	18619.	19189.
MAY		12902.	12555.	13100.	13645.
JUNE		6206.0	5946.6	6245.6	6544.6
JULY		4422.3	3968.4	4412.3	4856.3
AUG		5204.7	4331.9	5753.0	7174.1
SEPT		3476.6	3358.6	3825.1	4291.6
VARIANCE					
OCT		0.44766E 08	0.37863E 08	0.16768E 09	0.29750E 09
NOV	*	0.44235E 08	0.47225E 08	0.12736E 09	0.20749E 09
DEC	*	0.85030E 08	0.93678E 08	0.12654E 09	0.15941E 09
JAN		0.13446E 09	0.11533E 09	0.13715E 09	0.15898E 09
FEB		0.65825E 08	0.63467E 08	0.67948E 08	0.72429E 08
MAR		0.13563E 09	0.12862E 09	0.15256E 09	0.17650E 09
APR	*	0.93113E 08	0.94692E 08	0.10765E 09	0.12062E 09
MAY		0.69867E 08	0.63977E 08	0.77995E 08	0.92012E 08
JUNE		0.25707E 08	0.25498E 08	0.39147E 08	0.52796E 08
JULY		0.38531E 08	0.25069E 08	0.60732E 08	0.96396E 08
AUG		0.49518E 08	0.0	0.28833E 09	0.86170E 09
SEPT		0.12527E 08	0.0	0.63365E 08	0.15239E 09
SKEWNESS					
OCT	*	2.4133	3.7881	4.9313	6.0744
NOV	*	1.2122	2.7509	3.5231	4.2953
DEC	*	1.6956	1.7555	2.4178	3.0801
JAN		1.2298	1.0668	1.2909	1.5150
FEB		-0.26947E-01	-0.70420E-01	0.29215E-01	0.12885
MAR	*	0.77923	0.92204	1.2621	1.6023
APR	*	0.64720	1.0370	1.2333	1.4296
MAY	*	1.1037	1.1909	1.6717	2.1525
JUNE	*	1.8296	2.6519	3.6861	4.7202
JULY	*	3.3389	3.6314	4.9127	6.1940
AUG	*	3.4745	3.6951	4.8278	5.9605
SEPT	*	2.3229	2.6872	4.0165	5.3457

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2-14 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT STATION 4, TRANSFORMATIONS USED LOGARITHMIC AND WILSON-HILFERTY

STATISTIC NAME/ MONTH	HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
MEAN				
OCT	58435.	55389.	60677.	65965.
NOV	64416.	60949.	64650.	68351.
DEC	0.10419E 06	0.10143E 06	0.10783E 06	0.11424E 06
JAN	0.14535E 06	0.13776E 06	0.14399E 06	0.15022E 06
FEB	0.16026E 06	0.15632E 06	0.16040E 06	0.16448E 06
MAR	0.22760E 06	0.22381E 06	0.23024E 06	0.23667E 06
APR	0.17181E 06	0.17012E 06	0.17545E 06	0.18078E 06
MAY	0.12347E 06	0.12108E 06	0.12525E 06	0.12942E 06
JUNE	70527.	66675.	69954.	73234.
JULY	46867.	44891.	46595.	48298.
AUG	60249.	53248.	60434.	67620.
SEPT	42077.	39939.	42263.	44587.
VARIANCE				
OCT	0.33047E 10	0.16116E 10	0.76484E 10	0.13685E 11
NOV	0.24803E 10	0.23877E 10	0.36031E 10	0.48185E 10
DEC *	0.63783E 10	0.66701E 10	0.88095E 10	0.10949E 11
JAN	0.94416E 10	0.75325E 10	0.88868E 10	0.10241E 11
FEB	0.51934E 10	0.47148E 10	0.51087E 10	0.55026E 10
MAR	0.10979E 11	0.92144E 10	0.11407E 11	0.13601E 11
APR	0.68724E 10	0.65575E 10	0.75998E 10	0.86421E 10
MAY	0.37967E 10	0.33662E 10	0.39080E 10	0.44498E 10
JUNE	0.21754E 10	0.15319E 10	0.23063E 10	0.30807E 10
JULY	0.10589E 10	0.72377E 09	0.10625E 10	0.14013E 10
AUG	0.46926E 10	0.0	0.90254E 10	0.19325E 11
SEPT	0.13985E 10	0.96061E 09	0.20988E 10	0.32370E 10
SKEWNESS				
OCT *	2.4976	2.8048	4.1428	5.4808
NOV *	1.1730	1.8034	2.4952	3.1869
DEC	1.5026	1.4056	2.2051	3.0046
JAN	1.3247	0.96363	1.1609	1.3582
FEB *	0.17614E-01	0.21625E-01	0.13763	0.25363
MAR *	0.82445	0.93025	1.3014	1.6725
APR *	0.60374	0.85895	1.0818	1.3047
MAY *	0.84292	0.87584	1.1560	1.4362
JUNE	2.2070	2.0389	2.7117	3.3844
JULY	2.4079	1.8893	2.6177	3.3462
AUG *	2.5153	2.9998	3.9740	4.9481
SEPT	2.4045	2.4034	3.4833	4.5632

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

TABLE A2-15 COMPARISON OF SYNTHETIC AND HISTORIC STATISTICS AT ALL STATIONS, TRANSFORMATIONS USED LOGARITHMIC AND WILSON-HILFERTY

STATISTIC NAME/ STATIONS	HISTORIC VALUE	CONFIDENCE INTERVAL LOWER BOUND	SYNTHETIC AVERAGE	UPPER BOUND
CROSS CORRELATION				
1 1	1.0000	1.0000	1.0000	1.0000
2 1	* 0.83641	0.80504	0.81703	0.82902
3 1	0.77186	0.75858	0.77247	0.78636
4 1	* 0.92597	0.89525	0.90276	0.91027
2 2	1.0000	1.0000	1.0000	1.0000
3 2	0.84952	0.82711	0.83959	0.85206
4 2	0.86351	0.84398	0.85406	0.86414
3 3	1.0000	1.0000	1.0000	1.0000
4 3	0.89932	0.88882	0.89584	0.90287
4 4	1.0000	1.0000	1.0000	1.0000
SERIAL CORRELATION				
1 1	* 0.30250	0.36084	0.38298	0.40512
2 1	* 0.27811	0.28789	0.31425	0.34062
3 1	* 0.27170	0.27578	0.30307	0.33036
4 1	* 0.28849	0.35263	0.37839	0.40416
1 2	* 0.24491	0.31570	0.34736	0.37901
2 2	* 0.29417	0.33195	0.36405	0.39614
3 2	* 0.26159	0.27607	0.31000	0.34393
4 2	* 0.24731	0.33492	0.36823	0.40154
1 3	* 0.25316	0.29094	0.32332	0.35571
2 3	0.27622	0.27264	0.30531	0.33799
3 3	0.30842	0.29812	0.33080	0.36349
4 3	* 0.27039	0.33719	0.37050	0.40382
1 4	0.32481	0.32170	0.34851	0.37532
2 4	0.32704	0.28864	0.31751	0.34638
3 4	* 0.34923	0.28871	0.31749	0.34627
4 4	* 0.34517	0.36051	0.38898	0.41746

* INDICATES HISTORIC VALUE OUTSIDE CONFIDENCE INTERVAL

SYSTEMS ANALYSIS APPLIED TO RESERVOIR DESIGN IN THE JAMES RIVER BASIN

by

Erik Somers Hougland

(ABSTRACT)

A probabilistic linear programming model was used to find preliminary designs for two multi-purpose reservoirs in the upper James River basin. Requirements of flood control, water quality maintenance, and recreation in the upper and middle basins were considered through the year 2020. The preliminary designs were then evaluated by simulation using synthetic streamflow. A technique for generating synthetic streamflows was developed which combined features of several existing models.

Results showed that for water quality requirements to be met through 2020 in the middle basin (Lynchburg), 98% BOD_5 removal for all waste discharges will be required by the year 1980, even with both reservoirs in operation. In the upper basin (Covington), water quality requirements cannot be met in 1980 or thereafter even with 98% BOD_5 removal and the upper reservoir in operation.