

A SYNTHETIC HYDROLOGIC FLOW MODEL FOR
THE UPPER JAMES RIVER BASIN

by

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Thesis submitted to the Graduate Faculty of the
Virginia Polytechnic Institute
in candidacy for the degree of
MASTER OF SCIENCE
in
Civil Engineering

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October 28, 1966
Blacksburg, Virginia

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INTRODUCTION

The increasing demand by government, industry, and individuals for more and better things has caused a progressively fuller utilization of natural resources. In recent times man has endeavored to achieve maximum gains from available materials through careful scientific studies.

Water is probably a nation's most valuable natural resource, as it is utilized by the whole populace of any country. There was a time when the supply of clean water far exceeded demands for its use. This is no longer true. The recent water shortage in the Northeastern United States pointed out our dependence upon water resources to keep this nation prospering.

In the spring months we may be blessed by an abundance of water, but often this abundance causes an excessive, unregulated flow in our river basins. In the summer, we tend to lack a dependable supply of water of high quality. During periods of low flow, our rivers tend to become polluted or contaminated, and "fish kills" may appear. Sometimes problems relating to water quality are caused by inadequate sewage and industrial waste treatment. At other times these problems are caused by lack of correct flow regulation.

Our economic growth must, to some extent, depend upon future economic exploitation of rivers as water resources. Rivers are capable of producing billions of kilowatts of electricity. Farmers utilize the river in dry months to irrigate their lands. A proper regulation device can augment low flows in the summer and prevent loss

of life and property from floods during spring months. A lake impounded by a dam provides recreational areas and a refuge for wild-life. A river is also a valuable system component for disposing of treated wastes. To achieve maximum benefits from a river, regulation devices, based upon sound engineering and economic principles, must be designed and installed.

The flow patterns and quantities of a river are constantly changing. Rivers go through unpredictable dry and wet years, which are years of abnormally high or low flows. The flow in a river is usually highest during March and April after the spring thaws and rains. The monthly mean flow usually decreases through the summer and reaches a yearly minimum around October, at which time it starts increasing. The solution to the problem of variable flow is to store water from times of high flow to augment the periods of low flow.

The most important structures for the regulation of surface runoff are dams. Man has used regulation devices for three or four millenia in controlling floods and droughts. Ingenious, economical methods of design and construction have been developed for many types of sites. The method of estimating the proper size impoundment for a given stream, and target pattern of draft, is more or less based on "rules of thumb" that are at present more of an art than a science.

For engineering-economic analysis, an idea of future conditions or flows of the river in question is needed in order to achieve the

ultimate aim of any river basin project, and thereby serve civilization to the maximum extent possible. The optimum design may be defined as the system which realizes the most total benefits at the least cost. Before the optimum design can be achieved, future conditions should be known. This is impossible. Engineers must then try to estimate future flows and flow sequences. They have always done this by studying the historical records of the river and assuming that the same events will occur again. The probability of the historical sequence of flows reoccurring in the future is almost zero. The probability and possibility of various combinations of flows during the economic life of the structure should be fully analyzed in order to secure a reasonable basis for design.

The problem now becomes one of finding a method or technique of generating artificial flows which are characteristic of the river in question. The synthetic hydrology can then be analyzed in terms of possible future flow.

The monthly flow in a river appears to be serially correlated to the previous month's flow. The runoff is also proportional to the amount of rainfall. The object of this thesis is the synthetic generation of possible future flows in the James River at Buchanan, Virginia, through the utilization of existing records of precipitation and runoff, in order to find confidence limits on the dependable flow for a specified reservoir size.

The adequate development of water resources requires the use of planning techniques which depend to a large extent upon reliable

estimates of the probabilities associated with key hydrologic variables. The most important of these are estimates of the variability of annual stream flow and the frequency of occurrence of floods and droughts. Inaccurate knowledge of these characteristics can result in serious economic and engineering errors in a water resource development project (18).

LITERATURE REVIEW

The most common method for analyzing the relationship between reservoir inflow, desired draft, and storage capacity is that of W. Rippl (30,32). Rippl's method which is based on the mass diagram, which is essentially a chronological graph of cumulative flows known to have occurred, assumes that both inflows and outflows are known functions of time. This method gives the minimum effective storage required such that no water shortage will occur during the time period under consideration, which is usually the recorded historical record of the stream. Since the analysis is necessarily based on the historical record, it is quite unlikely that the same flow sequence will occur again during the active life of the completed structure.

It had been assumed that the longer the duration of stream flow records, the more accurate the analysis would be (30), but this was indicated to be false by Mr. H. E. Hurst in 1951 (15,17). Hurst first became concerned with the fallacies of the mass diagram when investigating the storage required in the Great Lakes of the Nile River. The length of time chosen as a basis of the estimates of storage being 100-years. Hurst began his investigation by studying the discharge of the Nile River at Aswan, the proposed reservoir site. The 75-year record of flow was studied from three points or sections of record. Hurst showed that during the first 38 years, a yield of 103 units per year could be obtained, and would require 201 units of storage; during the next 37 years a yield of 83 units

could be obtained and would require 83 units of storage; and during the entire 75 years a yield of 93 units per year could be obtained, but this would require 476 units of storage. This suggests that the longer the historical record, the greater the storage required by an analysis employing the Rippl mass diagram.

When long records of stream flow in the United States are analyzed, it is found that there are differences in storage requirements if the two halves of the record are analyzed separately (2). This shows a need for a method of analyzing stream flow that is not so highly dependent on the exact sequence of recorded historical flows.

Hydrologists have long recognized the desirability of extending hydrologic records by synthetic means. As early as 1914, Hazen (14) combined the annual flows from 14 different streams to produce an artificial record of 300-years. The streams used were from large and small basins in both humid and semi-arid areas. Due to the mixing of flow records from different streams, the synthetic 300-year sequence was not applicable to any one location. In fact, the validity of Hazen's method is open to question (31). Hazen did invent probability paper on which he plotted different storage capacities and suggested picking the storage which would yield the desired guaranteed minimum flow 95 per cent of the time.

In 1927 Sudler (7) expanded on Hazen's work because he was not satisfied with Hazen's probability approach. Sudler utilized historic flows and artificial flows which were obtained by Hazen's

approach, and assigned these values arbitrarily to a deck of 50 cards. The number of entries of any particular value being governed by its frequency of occurrence in the mixed record. The cards were then shuffled and drawn without replacement to produce a flow sequence of 50 years. He repeated the process 20 times to obtain flows for 1000 years. This procedure is limited in application because each 50-year period has the same mean, standard deviation and range (31).

In 1954, Barnes (1) removed the limitation of Sudler's method by assuming that annual flows were distributed normally with the same mean and standard deviation as the historic record. Based on these three assumptions, Barnes synthesized a 1000-year record by using Monte Carlo techniques. This method is limited to streams which show a normal distribution of discharges and which do not show any serial correlation between stream flows during different periods (31).

Recent studies (6,12,19,25,37,38,31) have attempted to describe stream flow sequences by mathematical models which can reproduce special features of the historic record such as periodicities, and which model the effects of serial correlation. Of these, the most important contribution was made by Thomas and Fiering (37). They proposed that stream flows could be simulated by a simple linear relationship with previous flows. Their model was,

$$Q_{j+1} = Q_{j-1} + b_j(Q_j - Q_{j-1}) + T_j(T_{j+1})(1 - r_j^2)^{1/2} \quad \text{where;}$$

Q_i and Q_{i+1} = the stream flows during months (i) and (i+1),

Q_j and Q_{j-1} = the mean monthly flows during months (j) and (j-1),

b_j = a regression coefficient,

T_i = normal random variate with zero mean and unit standard deviation,

T_{j-1} = standard deviation of flows in month (j-1),

r_j = correlation coefficient between flows in months (j) and (j-1),

i runs sequentially from zero to the end of the period of synthesis

j runs cyclically from one to twelve, representing the months of the year.

The use of the Fiering and Thomas model will generate an artificial record of any length. It is limited by the assumption that the correlation between months with a lag greater than one is negligible, and the assumption that the serial correlation is linear. It is also limited in that negative flows can be generated, which must be set to zero or some arbitrary value.

Yagil (38) modified the Fiering and Thomas model to account for the correlation of periods greater than one month, and developed a separate equation for each month.

In 1961 a major study of the "Past and Probable Future Variations in Stream Flow in the Upper Colorado River" was completed (19,13,41 5,37). This study was made to help realize the effective operation of the Glen Canyon Dam and its optimum coordinated operation with

the Hoover Dam. The aim of this project was a scientific examination of the possibilities of forecasting future flow variations by means of synthetic hydrology based on statistical analyses. Some of the major findings of this Committee were:

1) that precipitation records were not significantly different from a series of random numbers (19);

2) that the historical stream flow records of the Colorado River were very close to random in character (19);

3) that there was a small amount of carry-over in discharge from year to year which was assumed to be caused by different kinds of storage (40,41,42);

4) that the persistence of stream runoff detected by statistical tests was small and that only adjacent water years appeared to be linked (42). Mr. Yevdjevich pointed out that even when the persistence effect is small, the number of effective, or independent, observations of the stream runoff are reduced about 40 percent.

5) Both the Julian and the Yevdjevich reports pointed out that there were no statistically significant periodicities, cycles, or trends which could be utilized in any synthetic hydrologic method (20,42).

6) Britton (5) examined three approaches to the derivation of a synthetic hydrology. These were the probability analysis of forecasting future runoff by Leopold (22), Hurst (15), and the Thomas-Fiering method (37). Each method was evaluated in its applicability to the Colorado River data. Britton concluded that none of

these methods was entirely satisfactory for dealing with the Colorado River runoff series (13). It was concluded that at the present time it was not possible to reliably forecast future annual flows by a method based solely on the extrapolation of existing hydrological data.

One of the recommendations of the Colorado Committee was the development or improvement of statistical methods to be used in hydrological studies, in order to replace the current techniques based exclusively on historical data. It was also recommended that the application of monthly serial correlation coefficients be studied further in relation to streamflow generation (13).

In 1965 Markovic (26) fitted five probability functions; normal, log-normal 2 parameter, log-normal 3 parameter, gamma 2 parameter, and gamma 3 parameter, to the distributions of annual precipitation and annual runoff in the United States and Canada. The Chi-square test for goodness of fit was used for the 2506 station samples involved in the investigation. The result of this study was that all five probability functions studied were applicable, and that all were equally suitable for fitting on observed station sample of annual precipitation data or annual river flow data. Markovic also stated that the distribution of annual precipitation and annual flow were both positively skewed, with the distribution of annual river flow being some what more skewed than the precipitation.

Analyses performed by Snyder (35) indicated that on many watersheds the present value of a hydrologic parameter may be a function

of conditions prevailing much earlier in time. He demonstrated that runoff from groundwater was dependent on rainfall which occurred as much as three years previously.

METHODS

The James River basin above Buchanan, Virginia was chosen for this study as it is essentially unregulated and the flows recorded are very representative of the virgin flow. The drainage area of this basin is 2084 square miles and the records are listed as good. The mean monthly flows for the period of October 1930 to September 1962 were taken from the U.S.G.S. Water Supply Papers.

This period was selected because the precipitation records before 1930 were not continuous. Six precipitation stations are present in the basin and the Thiessen method was utilized to find the total monthly rainfall for the basin.

A stepwise multiple regression library program, which was a modification of a program originally written by M. A. Efroymsen (10) of the Esso Research and Engineering Company, was used to find the best monthly model of streamflow. The general model was

$$Q_i = a + b_1f(P_i) + b_2f(Q_{i-1}) + b_3f(P_{i-1}) + b_4f \quad (\text{cross products})$$

where Q_i = mean monthly flow of month i

P_i = total basin precipitation for month i

Q_{i-1} = mean monthly flow for previous month

P_{i-1} = total basin precipitation for previous month

i = index running from 1 to 12

a = constant

b = coefficient

f = some function

The monthly models were chosen on the basis of degree of correlation as indicated by the correlation coefficient (r), where r is equal to the corrected sum of squares regression divided by the total corrected sum of squares.

The total monthly precipitations were fitted to a Pearson Type I and a Pearson Normal distribution. This was accomplished through the use of a modified version of the computer program, "Pearson Universal Random Distribution Generator" (PURGE), originally written by members of the IBM Scientific Computation Department, Cooper, Davis, and Dono (36). The distribution is fitted and parameters for the Pearson Curve with origin at the mean are printed. At this point, through the use of a random number generation option, 5000 random values from the monthly precipitation distribution were generated. The numbers were used sequentially as the first month's total precipitation for the James River basin above Buchanan, Virginia. The procedure was then repeated for the remaining eleven months. In all 5000 years of random monthly precipitation values were obtained.

The synthetic mean monthly flow for 5000 years was found by using the twelve separate monthly mean flow models with the random precipitations. The total 5000 year mean monthly flows were divided into fifty 100-year periods so that the dependable flow could be found for each of eight fixed reservoir sizes. The method utilized in finding the dependable flow is that of H. M. Morris (30). Flow duration curves for five of the fifty 100-year records were plotted and compared with the actual flow duration curves for the 32-year

period used in the development of the model and total period of recorded flows, which was 64 years.

The eight reservoir sizes chosen were 5, 10, 15, 20, 25, 30, 35, and 40 billion cubic feet of storage. The guaranteed dependable flow for each reservoir size for each of the fifty 100-year periods was found. The fifty dependable flows for each reservoir size for the Pearson Type I and for the Pearson Normal distribution were used to determine the 90 percent confidence limits on the dependable flow for a certain reservoir size.

RESULTS

The best mean monthly flow models were chosen by the stepwise multiple regression technique described in the previous section. The twelve separate monthly models in Fortran notation are found in the Appendix. The monthly flow models have mixed functions and have varying correlation coefficients (r) ranging from 0.55 for July to 0.92 for October. The average value of the correlation coefficient was 0.77. The model for May in Fortran notation was:

$$\text{FLO}(J,I) = -4.1086 + 1.2866 \text{ PREP}(J,I) + 0.54844 \text{ FLO}(J,I-1) + 0.5244 \text{ PREP}(J,I-1) - .03239 \times \text{PREP}(J,I) \times \text{FLO}(J,I-1) \times \text{PREP}(J,I-1)$$

where

$\text{FLO}(J,I)$ = mean monthly flow in $\text{cfs} \times 10^{-3}$ for the month of May

$\text{PREP}(J,I)$ = total precipitation for May in inches

$\text{FLO}(J,I-1)$ = mean monthly flow in $\text{cfs} \times 10^{-3}$ for the month of April

$\text{PREP}(J,I-1)$ = total precipitation for April in inches

I = index running from one to twelve denoting months of the year

J = index running from one to 5000 denoting year.

In order to fit the correct distribution, the (PURGE) subroutine had to find the first four moments for each of the monthly precipitation totals. These are listed in Table 1.

Table 1. Moments of the Monthly Precipitation.
Totals for the Period 1930-1962 for the
James River at Buchanan, Virginia.

Moment Month	1st Mean (in.)	2nd Variance	3rd Skewness	4th Kurtosis
January	2.85	2.12	3.44	18.29
February	2.78	0.77	-0.05	1.40
March	3.70	1.52	0.77	6.56
April	3.01	1.04	0.15	3.14
May	3.44	2.09	2.81	17.71
June	3.65	1.83	1.02	8.12
July	3.85	1.38	0.01	4.29
August	3.97	3.55	7.63	48.05
September	3.06	2.50	3.49	18.65
October	2.75	4.04	12.58	89.30
November	2.61	1.33	1.08	6.25
December	2.73	1.11	-0.10	3.65

A sample of the random precipitation from the Pearson Type I distribution is given in Table 2, page 24. An illustration of the Pearson Type I distribution for the June precipitation is given in Figure 1, page 26. A sample of the random monthly precipitation from the Pearson Normal distribution is given in Table 3, page 28. An illustration of the Pearson Normal distribution for the June precipitation is given in Figure 2, page 27.

The twelve monthly flow models were used to generate 5000-years of synthetic mean monthly flows. If the flows were negative or zero, they were set equal to the minimum mean monthly flow of record. Examples of the monthly synthetic flows obtained through the use of Pearson Type I distribution are given in Table 4, page 30. Examples of the monthly synthetic flows obtained through the use of the Pearson Normal distribution are given in Table 5, page 32.

The 5000-year synthetic record of mean monthly flows was divided into fifty separate 100-year records for the purpose of analysis. The average mean monthly flows for the fifty 100-year synthetic records of flow from the Pearson Type I and the Pearson Normal Distributions are presented in Tables 6 and 7 respectively.

TABLE 2. SAMPLE MONTHLY PRECIPITATION TOTALS
OBTAINED FROM THE PEARSON TYPE I DISTRIBUTION
IN INCHES.

JAN.	FEB.	MAR.	APR.	MAY	JUNE
3.91	2.93	3.59	2.08	3.03	2.99
2.61	2.03	3.91	3.53	4.74	3.57
4.60	3.23	2.15	3.41	1.86	3.43
1.30	2.64	2.84	3.15	3.39	4.45
1.79	2.17	1.53	0.01	5.48	4.28
2.27	2.21	2.19	4.05	3.80	6.21
3.43	1.90	2.85	2.67	1.96	3.28
2.63	2.48	3.32	2.98	4.21	3.47
3.82	1.89	4.54	4.07	1.35	2.00
5.18	3.99	1.29	6.16	5.83	1.93
1.63	1.80	3.68	3.28	5.63	2.39
4.60	3.65	3.55	3.23	1.93	2.84
1.52	2.54	1.66	2.36	3.46	4.03
3.39	1.39	3.46	3.11	2.37	4.58
2.31	3.79	3.14	1.51	2.79	5.82
7.44	3.84	4.78	2.70	3.16	2.37
3.36	2.48	3.60	1.92	3.72	3.68
4.28	0.57	5.73	2.09	3.36	1.69
3.78	4.02	3.88	3.81	4.42	1.83
4.73	3.81	2.37	3.45	3.73	3.51
3.36	2.34	2.85	4.81	1.56	3.42
5.02	2.11	3.13	1.84	4.00	3.34
3.76	3.83	2.30	4.33	4.44	4.05
2.92	4.29	2.88	2.66	2.63	3.37
7.59	4.19	3.91	2.19	2.75	5.08
4.83	1.56	2.34	3.83	1.57	2.38
4.24	3.20	3.34	2.53	5.16	4.83
1.22	1.54	3.73	1.83	4.49	4.51
3.68	1.74	3.22	3.42	2.83	2.53
1.28	1.34	4.49	3.85	1.74	4.72
2.52	3.47	3.70	4.41	2.40	2.32
4.01	4.57	5.36	1.70	2.91	5.81
1.99	2.70	3.38	2.45	2.73	2.20
1.57	1.23	2.95	2.96	2.76	6.11
1.89	4.01	3.36	3.97	2.65	3.29
3.19	3.43	4.10	3.92	6.10	7.20
2.34	3.70	5.18	2.95	4.89	3.00
1.67	2.25	2.85	3.14	4.51	5.25
1.31	1.96	3.28	3.19	4.75	3.54

CONTINUED ON NEXT PAGE

TABLE 2. SAMPLE MONTHLY PRECIPITATION TOTALS
OBTAINED FROM THE PEARSON TYPE I DISTRIBUTION
IN INCHES.

JULY	AUG.	SEPT	OCT.	NOV.	DEC.
2.94	4.44	2.55	3.39	3.22	1.25
4.08	1.91	1.50	2.29	4.79	2.57
1.56	2.40	5.36	0.83	3.72	4.03
4.93	5.10	4.82	2.19	2.56	3.82
3.96	6.78	2.60	1.22	2.09	2.20
3.59	8.36	4.09	1.13	5.87	0.57
3.56	3.21	1.57	2.12	2.61	3.30
3.36	2.31	1.39	1.93	3.81	1.52
2.66	3.71	4.55	3.89	2.51	2.35
1.81	3.65	3.49	3.13	1.45	3.87
3.81	1.92	1.98	1.03	2.54	3.28
4.39	6.10	5.48	0.85	3.14	3.24
3.48	1.99	1.33	1.05	1.76	2.84
3.65	1.90	2.10	3.01	2.04	1.18
4.18	3.57	1.37	7.92	0.44	2.31
5.35	2.16	4.73	0.88	1.54	3.61
4.55	2.23	1.85	2.68	5.57	2.66
6.44	7.37	3.37	1.06	3.64	1.48
3.64	6.51	3.51	1.37	2.61	2.53
4.08	5.55	5.16	3.66	2.98	1.33
5.85	8.04	3.69	2.74	2.31	1.37
3.50	2.39	3.36	2.32	1.35	3.57
1.81	2.71	2.49	4.49	1.06	0.99
4.06	7.19	1.96	2.62	4.09	2.81
3.35	5.73	6.15	0.86	3.08	3.34
4.40	2.14	4.53	1.96	1.48	1.75
4.70	3.10	1.83	2.35	3.39	3.23
1.94	6.59	4.31	1.94	4.33	2.38
3.53	3.46	7.16	0.86	1.32	4.21
2.41	2.36	5.94	6.57	1.44	3.41
2.85	2.02	1.70	4.38	1.67	1.18
4.00	3.14	1.65	2.08	1.36	1.90
5.79	1.99	1.34	0.95	2.30	3.16
3.78	2.87	1.41	1.32	2.89	1.98
3.84	3.51	4.25	1.32	1.90	2.29
5.32	4.08	5.46	1.11	1.73	0.25
2.58	6.63	5.26	0.92	3.12	1.75
4.60	5.58	4.62	1.04	2.48	3.51
2.85	5.78	2.36	1.62	1.88	0.22

Figure 1. Precipitation totals for June for the James River Basin above Buchanan, Virginia, for the period 1930 to 1932, fitted to a Pearson Type I distribution.

DISTRIBUTION GENERATOR

PEARSON CURVE TYPE ONE

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MU(3)	1.01826622	1.03285122	
MU(4)	8.12183309	8.38617706	
BETA 1	0.16839108	0.16299521	
BETA 2	2.41760305	2.39679140	
KAPPA	-0.08072754	-0.07694115	

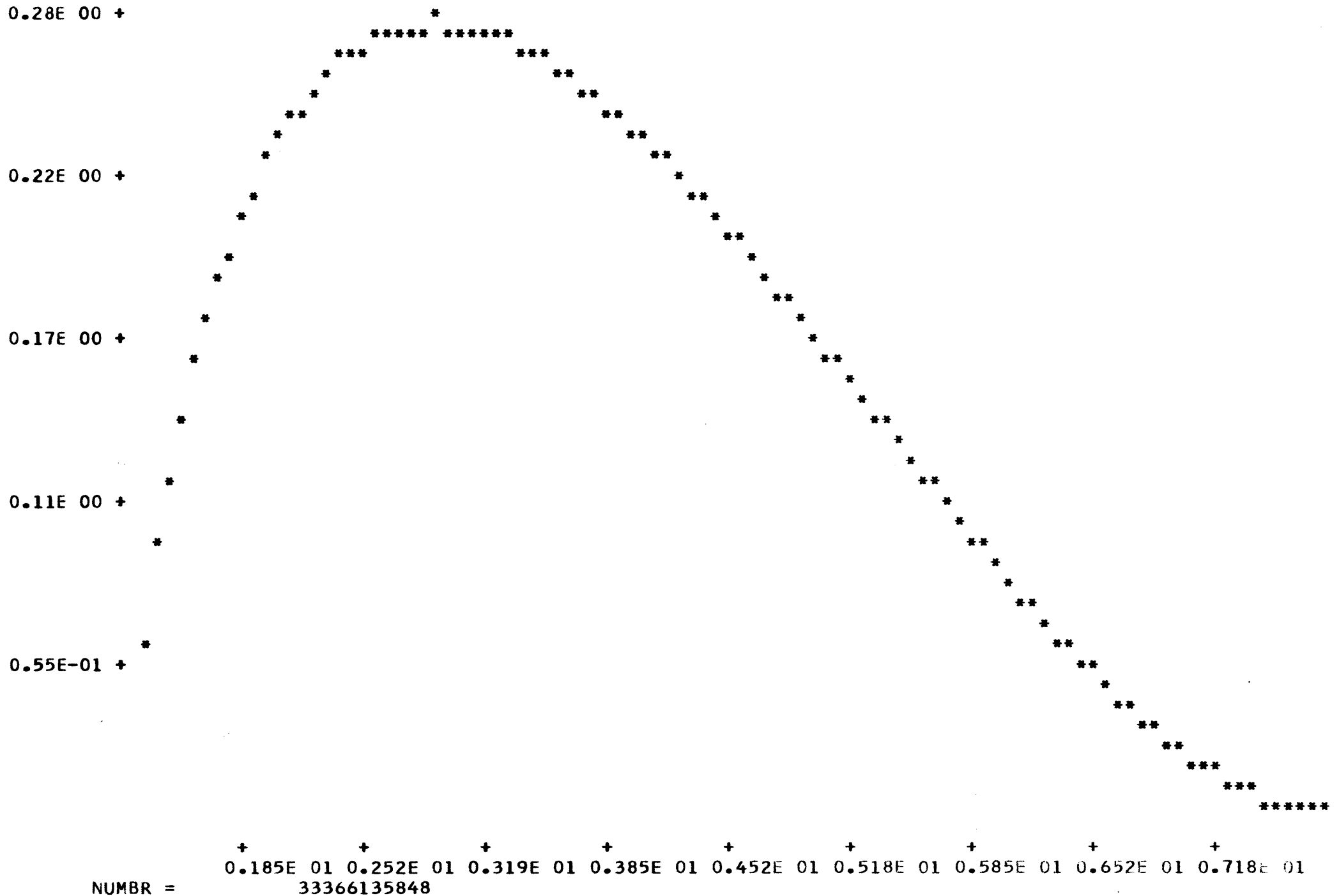


Figure 2. Precipitation totals for June for the James River Basin above Buchanan, Virginia, for the period 1930 to 1962, force-fitted to a Pearson Normal distribution.

DISTRIBUTION GENERATOR

THIS IS A NORMAL DISTRIBUTION

C= 2.77066E 00 Y0= 3.38949E-01

MOMENTS	FROM ORIGINAL DATA	FROM GENERATED DATA	N= 5100
MEAN	3.85085714	3.86598507	
VARIANCE	1.38532783	1.42347825	
MU(3)	0.01010495	0.01801014	
MU(4)	4.28996658	6.02670288	
BETA 1	0.00003841	0.00011246	
BETA 2	2.23536676	2.97425440	
KAPPA	-0.00001925	-0.00162740	

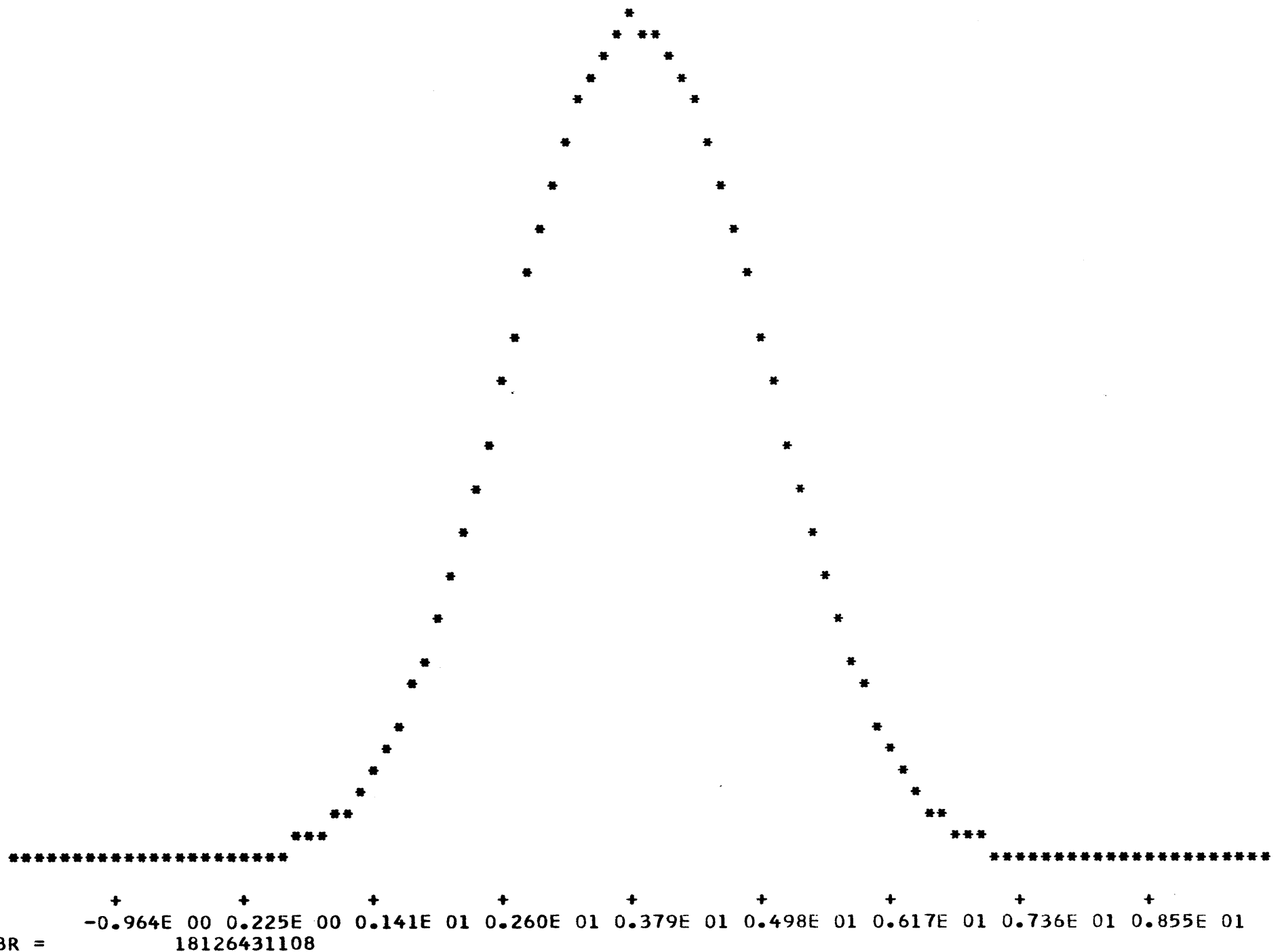
0.35E 00 +

0.28E 00 +

0.21E 00 +

0.14E 00 +

0.69E-01 +



NUMBR =

18126431108

TABLE 3. SAMPLE MONTHLY PRECIPITATION TOTALS
OBTAINED FROM THE PEARSON NORMAL DISTRIBUTION
IN INCHES.

JAN.	FEB.	MAR.	APR.	MAY	JUNE
4.03	2.90	3.69	2.10	3.27	3.18
2.96	2.10	4.00	3.54	4.80	3.71
4.51	3.18	2.10	3.43	1.71	3.59
0.97	2.65	2.94	3.17	3.64	4.45
2.00	2.22	1.12	-0.40	5.35	4.30
2.62	2.26	2.16	4.04	4.02	6.00
3.67	1.97	2.95	2.70	1.88	3.45
2.99	2.51	3.43	3.01	4.37	3.63
3.97	1.95	4.56	4.06	0.60	2.00
4.89	3.96	0.59	6.08	5.60	1.89
1.73	1.87	3.79	3.31	5.46	2.54
4.51	3.59	3.66	3.26	1.82	3.04
1.52	2.56	1.36	2.39	3.70	4.10
3.64	1.44	3.57	3.13	2.49	4.55
2.65	3.74	3.26	1.49	3.00	5.61
6.34	3.79	4.77	2.73	3.40	2.52
3.62	2.50	3.70	1.93	3.94	3.81
4.29	0.07	5.59	2.11	3.60	1.41
3.94	4.00	3.97	3.82	4.55	1.70
1.07	4.43	1.31	3.74	5.29	3.40
4.59	3.75	2.39	3.46	3.96	3.66
3.62	2.38	2.95	4.76	1.12	3.58
4.79	2.17	3.24	1.84	4.20	3.51
3.92	3.77	2.31	4.30	4.56	4.12
3.25	4.35	2.98	2.69	2.81	3.54
6.44	4.22	4.00	2.22	2.96	4.96
4.66	1.62	2.36	3.83	1.14	2.52
4.26	3.15	3.45	2.56	5.12	4.75
0.71	1.60	3.83	1.83	4.60	4.49
3.86	1.81	3.33	3.44	3.05	2.70
0.92	1.37	4.51	3.85	1.50	4.66
2.88	3.41	3.80	4.38	2.52	2.45
4.10	4.82	5.27	1.69	3.14	5.61
2.28	2.70	3.49	2.48	2.94	2.29
1.63	1.25	3.06	2.99	2.96	5.89
2.14	3.99	3.48	3.96	2.83	3.46
3.48	3.36	4.17	3.92	5.78	7.34
2.69	3.64	5.11	2.98	4.92	3.19
1.81	2.30	2.95	3.16	4.62	5.11

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TABLE 3. SAMPLE MONTHLY PRECIPITATION TOTALS
OBTAINED FROM THE PEARSON NORMAL DISTRIBUTION
IN INCHES.

JULY	AUG.	SEPT	OCT.	NOV.	DEC.
3.05	4.84	2.97	3.93	3.32	1.27
4.06	0.06	1.52	2.99	4.56	2.56
1.32	2.60	5.02	-2.32	3.74	4.03
4.83	5.31	4.66	2.88	2.71	3.82
3.95	6.40	3.02	1.37	2.22	2.19
3.63	7.43	4.16	1.12	5.32	0.62
3.60	3.75	1.67	2.81	2.76	3.28
3.43	2.39	1.18	2.59	3.81	1.54
2.78	4.24	4.47	4.28	2.66	2.35
1.74	4.19	3.73	3.73	1.43	3.87
3.82	0.24	2.35	0.74	2.69	3.27
4.33	5.97	5.11	-1.13	3.25	3.22
3.53	1.10	0.94	0.84	1.84	2.83
3.68	-0.79	2.50	3.64	2.17	1.21
4.15	4.12	1.12	6.57	-0.55	2.30
5.26	1.96	4.60	-0.35	1.56	3.60
4.47	2.19	2.17	3.35	5.11	2.65
7.13	6.77	3.64	0.88	3.67	1.50
3.68	6.23	3.75	1.72	2.76	2.52
4.05	5.61	4.89	4.12	3.10	1.35
5.89	7.21	3.88	3.41	2.45	1.38
3.55	2.58	3.64	3.02	1.29	3.56
1.75	3.13	2.91	4.66	0.85	1.02
4.04	6.66	2.32	3.31	4.03	2.80
3.42	5.73	5.61	-0.66	3.19	3.33
4.34	1.91	4.45	2.62	1.48	1.76
4.61	3.63	2.14	3.04	3.46	3.22
1.93	6.28	4.31	2.60	4.21	2.37
3.57	4.01	6.52	-0.76	1.25	4.23
2.52	2.52	5.44	5.86	1.42	3.40
2.96	1.36	1.93	4.60	1.72	1.20
3.99	3.67	1.84	2.76	1.31	1.90
5.80	1.14	1.00	0.32	2.44	3.15
3.79	3.35	1.24	1.61	3.03	1.98
3.85	4.06	4.27	1.60	2.00	2.28
5.23	4.56	5.09	1.04	1.80	0.31
2.70	6.30	4.96	0.05	3.23	1.76
4.52	5.63	4.52	0.80	2.63	3.50
5.33	2.92	3.77	5.80	1.70	4.04

TABLE 4. EXAMPLES OF THE MONTHLY SYNTHETIC FLOWS
OBTAINED THROUGH THE USE OF THE PEARSON TYPE I
DISTRIBUTION OF PRECIPITATION, IN CFS.

JAN.	FEB.	MAR.	APR.	MAY	JUNE
4863.	5529.	3563.	4353.	3076.	1230.
3120.	3297.	3364.	8374.	2978.	508.
5427.	2786.	3545.	1054.	2332.	1305.
2830.	5500.	3461.	6963.	3359.	1498.
3663.	7337.	4802.	2376.	1436.	893.
8589.	10509.	6932.	825.	872.	1447.
4647.	1831.	2228.	4667.	1567.	907.
4609.	4726.	4579.	1649.	4068.	2123.
1319.	1898.	3909.	722.	2831.	1719.
3712.	2340.	3445.	3212.	2079.	1159.
1473.	1799.	4702.	2891.	1111.	645.
1778.	4730.	5183.	5748.	2474.	1130.
3238.	6730.	8539.	113.	573.	2881.
1534.	3452.	4206.	1501.	1191.	1247.
1426.	5509.	5061.	4655.	2346.	912.
811.	3261.	5436.	3391.	5026.	13346.
1908.	5293.	7503.	627.	3786.	1446.
1742.	3272.	3335.	3005.	3612.	2497.
1907.	3618.	3856.	2700.	3835.	1458.
1976.	4712.	4621.	914.	1021.	1215.
371.	555.	2412.	6057.	3321.	6838.
3556.	4655.	4393.	162.	649.	3600.
523.	5107.	3191.	945.	2554.	1553.
4869.	5204.	3357.	1855.	869.	1103.
3250.	954.	1511.	3016.	1488.	829.
5320.	3229.	6606.	187.	231.	4044.
2411.	1493.	3198.	1539.	2291.	1214.
371.	1920.	2571.	3049.	1311.	2337.
2865.	2875.	5289.	2129.	5267.	1255.
334.	2953.	3280.	4281.	3777.	1617.
5769.	4563.	5284.	5338.	1860.	2560.
629.	1393.	6693.	1814.	1489.	742.
443.	924.	4383.	582.	2107.	1366.
3313.	3359.	6928.	672.	1171.	858.
3664.	4339.	4273.	3549.	1028.	761.
5878.	6893.	6096.	1677.	3311.	2045.
5457.	2657.	3588.	3469.	3228.	1431.
641.	4014.	4353.	1298.	1157.	1086.
3119.	215.	3446.	3734.	1247.	1148.

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TABLE 4. EXAMPLES OF THE MONTHLY SYNTHETIC FLOWS
OBTAINED THROUGH THE USE OF THE PEARSON TYPE I
DISTRIBUTION OF PRECIPITATION, IN CFS.

JULY	AUG.	SEPT	OCT.	NOV.	DEC.
764.	978.	498.	132.	239.	252.
353.	3102.	1050.	1203.	2319.	4065.
673.	1660.	417.	294.	527.	1027.
733.	1728.	793.	568.	949.	2152.
916.	1004.	492.	1013.	1730.	2017.
733.	303.	413.	1365.	1492.	3872.
520.	2810.	487.	450.	305.	517.
1256.	1886.	576.	1085.	1274.	781.
1092.	303.	422.	494.	402.	818.
574.	312.	414.	1665.	3589.	4662.
2408.	1430.	417.	294.	491.	1243.
820.	303.	468.	13.	62.	305.
589.	682.	2677.	763.	1293.	2331.
1214.	373.	807.	1584.	2525.	1959.
622.	303.	606.	2911.	1772.	3451.
902.	1352.	445.	362.	706.	1855.
671.	100.	419.	737.	694.	981.
743.	360.	440.	895.	1246.	928.
756.	1258.	2103.	804.	570.	683.
765.	612.	434.	585.	1316.	871.
51.	6252.	592.	2760.	1535.	2209.
1402.	1338.	412.	826.	903.	2093.
666.	746.	558.	280.	202.	360.
1260.	2353.	502.	768.	1106.	888.
984.	770.	812.	1157.	1759.	2403.
498.	227.	606.	2849.	2522.	6365.
745.	147.	551.	514.	680.	1278.
1217.	303.	1439.	2515.	2052.	4196.
692.	1524.	712.	2028.	2220.	1223.
1212.	1142.	541.	239.	260.	736.
748.	1746.	830.	1225.	1909.	4139.
1195.	2360.	1211.	1102.	1119.	1912.
708.	1119.	1881.	821.	1133.	1623.
874.	2340.	1188.	807.	637.	1043.
883.	1317.	556.	342.	507.	1097.
542.	439.	475.	25.	115.	354.
1617.	1028.	424.	294.	623.	1418.
797.	1763.	592.	735.	585.	1286.
1142.	880.	3891.	78.	160.	238.

TABLE 5. EXAMPLES OF THE MONTHLY SYNTHETIC FLOWS
OBTAINED THROUGH THE USE OF THE PEARSON NORMAL
DISTRIBUTION OF PRECIPITATION, IN CFS.

JAN.	FEB.	MAR.	APR.	MAY	JUNE
4554.	4412.	4895.	934.	1503.	1122.
2746.	2943.	4668.	2662.	3916.	1489.
5220.	4816.	2895.	4338.	1445.	524.
845.	2758.	3466.	3000.	2758.	1379.
2598.	4038.	1273.	700.	3003.	1739.
2301.	3124.	2424.	5459.	3305.	4103.
2787.	2486.	3214.	2147.	552.	617.
3305.	3954.	4306.	2240.	3369.	1400.
3782.	2593.	5238.	3280.	332.	883.
5593.	5971.	1086.	7073.	2364.	1386.
1993.	2942.	4312.	2410.	4560.	1402.
4273.	5140.	5252.	2435.	810.	713.
1182.	2981.	1415.	2648.	2602.	1282.
3219.	1741.	3641.	2310.	1417.	923.
2195.	5431.	4797.	750.	831.	2427.
6624.	6035.	7108.	699.	1876.	1290.
2905.	3388.	4545.	799.	2218.	1309.
5020.	412.	4980.	282.	1719.	1627.
3624.	5888.	6019.	3204.	3700.	1589.
873.	5676.	2149.	5214.	4177.	1463.
4798.	5484.	3573.	4365.	3257.	1299.
3529.	3378.	3518.	8158.	2895.	302.
5306.	2959.	3742.	995.	2556.	1352.
2979.	5424.	3440.	6865.	3417.	1549.
4062.	7379.	4981.	2313.	1625.	933.
6589.	6864.	6345.	803.	1128.	1428.
4562.	1953.	2286.	4689.	1273.	728.
4892.	4791.	4733.	1585.	4020.	2043.
811.	1295.	3932.	682.	2964.	1738.
3614.	2337.	3609.	3146.	2271.	1162.
1116.	1543.	4697.	2870.	877.	496.
2295.	4861.	5326.	5455.	2473.	1110.
3622.	7174.	8632.	121.	864.	2499.
1927.	3715.	4410.	1447.	1422.	1257.
779.	412.	2710.	2443.	1911.	3140.
1812.	5792.	5277.	4457.	2437.	947.
1366.	4049.	5661.	3255.	4778.	15269.
2073.	5159.	7350.	691.	3835.	1449.
1529.	3455.	3990.	2633.	3893.	1486.

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TABLE 5. EXAMPLES OF THE MONTHLY SYNTHETIC FLOWS
OBTAINED THROUGH THE USE OF THE PEARSON NORMAL
DISTRIBUTION OF PRECIPITATION, IN CFS.

JULY	AUG.	SEPT	OCT.	NOV.	DEC.
722.	1123.	545.	1425.	1896.	1268.
1105.	303.	493.	1043.	1972.	2627.
340.	233.	1376.	294.	703.	1862.
1528.	1495.	1066.	1380.	1598.	3444.
1257.	2034.	791.	676.	854.	1202.
1082.	3778.	1255.	679.	1711.	548.
612.	303.	436.	786.	1096.	2187.
923.	157.	417.	664.	1258.	1104.
505.	787.	945.	1888.	1933.	2440.
539.	1276.	662.	1478.	1010.	2514.
801.	303.	576.	162.	375.	930.
708.	1308.	1373.	294.	647.	1399.
989.	303.	436.	294.	421.	898.
942.	303.	690.	1647.	1510.	1031.
1561.	1424.	505.	2803.	734.	1213.
966.	219.	1180.	117.	200.	643.
1187.	17.	431.	960.	2028.	2760.
867.	7373.	955.	537.	1097.	968.
679.	1893.	860.	854.	1183.	1774.
1027.	1545.	1210.	1856.	2160.	1507.
1580.	3185.	1120.	1707.	1707.	1298.
381.	303.	684.	1231.	827.	1984.
619.	799.	487.	1584.	697.	496.
1207.	2044.	858.	1755.	2572.	3582.
758.	1351.	1698.	151.	409.	1006.
1457.	303.	1105.	1294.	957.	1075.
657.	351.	424.	813.	1335.	2474.
763.	2490.	1034.	1276.	2149.	2611.
1167.	1025.	2624.	243.	273.	980.
618.	249.	1711.	2248.	1324.	2737.
534.	303.	451.	1576.	1210.	871.
732.	516.	427.	721.	576.	785.
2782.	1083.	435.	294.	543.	1208.
723.	462.	439.	294.	604.	808.
1328.	1788.	854.	801.	883.	1294.
1113.	1138.	1292.	721.	766.	152.
19.	9497.	1331.	316.	766.	862.
1071.	1588.	1029.	560.	875.	1957.
2243.	1246.	706.	2371.	1578.	3711.

Table 6. Average 100-year flows, generated through the use of the Pearson Type I distribution, in cubic feet per second.

2124	2130	2070	2175	2165
2040	2193	2170	2235	2122
2097	2106	2025	2157	2105
2037	1999	2044	1978	2139
2044	2160	2037	2059	2086
2184	2023	2120	2148	2136
2238	2103	2072	2103	1933
2096	2033	2168	2103	1984
2131	2157	2054	2051	2047
2623	2101	2115	2118	2177

Table 7. Average 100-year flows, generated through the use of the Pearson Normal distribution, in cubic feet per second.

2160	2177	2113	2226	2241
2101	2173	2208	2264	2120
2174	2145	2072	2206	2140
2101	2049	2116	2050	2183
2109	2197	2104	2123	2154
2278	2079	2221	2156	2226
2291	2172	2129	2159	2001
2168	2106	2237	2142	2061
2197	2269	2118	2116	2109
2234	2174	2152	2178	2260

The average mean monthly flow for the 32-year period used in construction of the monthly models was 2439 cfs. The average mean monthly flow for the total period of record, 64 years, was 2481 cfs. The flow duration curves for the 32 and 64 year historical record are presented in Figure 3, page 36, and Figure 4, page 37, respectively. Sample flow duration curves for the synthetic flows obtained through the use of the Pearson Type I and the Pearson Normal precipitation distributions are presented in Figures 5 through 9 and Figures 10 through 14 respectively.

The next step was to analyze each of the fifty 100-year synthetic flow records, assuming that a reservoir of specified capacity was in existence. The dependable flow for each reservoir size and for each 100-year period was estimated by the Rippl technique. The dependable flows utilizing the Pearson Type I distribution of rainfall are given in Table 8, page 48. The dependable flows utilizing the Pearson Normal distribution of rainfall are given in Table 9, page 50.

The mean dependable flows for each reservoir size for both synthetic flow models are compared with the dependable flow of the actual thirty-two year record in Figure 15, page 52. The mean dependable flows, expressed as a per cent of the average flow, for both synthetic series compared with the dependable flows for the thirty-two year record in Figure 16, page 53.

In Figure 17, page 54, 90 per cent confidence limits are placed on the dependable flows, expressed as a per cent of the average flow, for both synthetic flow models.

FIGURE 3. FLOW DURATION CURVE FOR THE JAMES RIVER
AT BUCHANAN, VIRGINIA, FOR THE PERIOD 1930 TO 1962

PERCENT	CFS
1.0	8418
3.4	7185
5.7	6360
8.1	6094
10.4	5500
12.8	5193
15.1	4763
17.4	4376
19.8	4120
22.1	3938
24.5	3703
26.8	3518
29.2	3252
31.5	3021
33.9	2800
36.2	2582
38.5	2417
40.9	2215
43.2	2129
45.6	2028
47.9	1923
50.3	1778
52.6	1664
54.9	1484
57.3	1315
59.6	1219
62.0	1098
64.3	1069
66.7	1001
69.0	934
71.4	850
73.7	778
76.0	720
78.4	648
80.7	610
83.1	549
85.4	515
87.8	488
90.1	458
92.4	419
94.8	403
97.1	366

FIGURE 4. FLOW DURATION CURVE FOR THE JAMES RIVER
AT BUCHANAN, VIRGINIA, FOR THE PERIOD 1898 TO 1962

PERCENT	CFS
1.0	9189
3.4	7399
5.7	6459
8.1	6045
10.4	5479
12.8	4989
15.1	4608
17.4	4345
19.8	4039
22.1	3887
24.5	3689
26.8	3472
29.2	3249
31.5	3019
33.9	2846
36.2	2669
38.5	2579
40.9	2439
43.2	2279
45.6	2156
47.9	2034
50.3	1859
52.6	1749
54.9	1579
57.3	1475
59.6	1339
62.0	1219
64.3	1149
66.7	1059
69.0	991
71.4	887
73.7	806
76.0	751
78.4	704
80.7	645
83.1	605
85.4	549
87.8	515
90.1	480
92.4	444
94.8	417
97.1	370

FIGURE 5. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON TYPE I DISTRIBUTION OF PRECIPITATION.

PERCENT	CFS
1.0	9087
3.5	6361
6.0	5448
8.5	4937
11.0	4644
13.5	4206
16.0	3854
18.5	3588
21.0	3356
23.5	3121
26.0	2849
28.5	2615
31.0	2419
33.5	2238
36.0	2078
38.5	1881
41.0	1726
43.5	1621
46.0	1535
48.5	1443
51.0	1380
53.5	1278
56.0	1211
58.5	1149
61.0	1092
63.5	1027
66.0	940
68.5	874
71.0	811
73.5	763
76.0	712
78.5	671
81.0	613
83.5	562
86.0	506
88.5	437
91.0	402
93.5	302
96.0	246
98.5	100

FIGURE 6. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON TYPE I DISTRIBUTION OF PRECIPITATION.

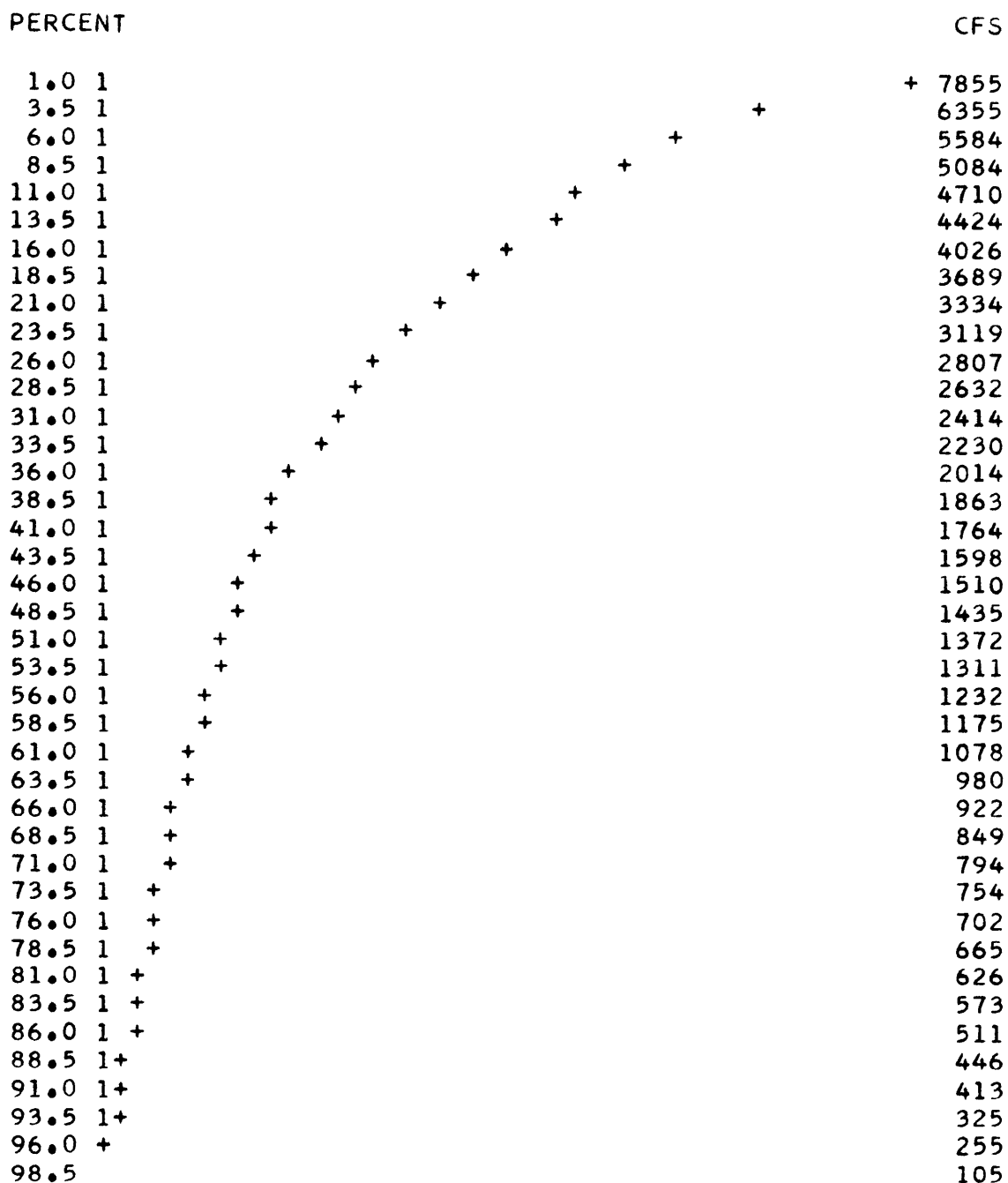


FIGURE 7. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON TYPE I DISTRIBUTION OF PRECIPITATION.

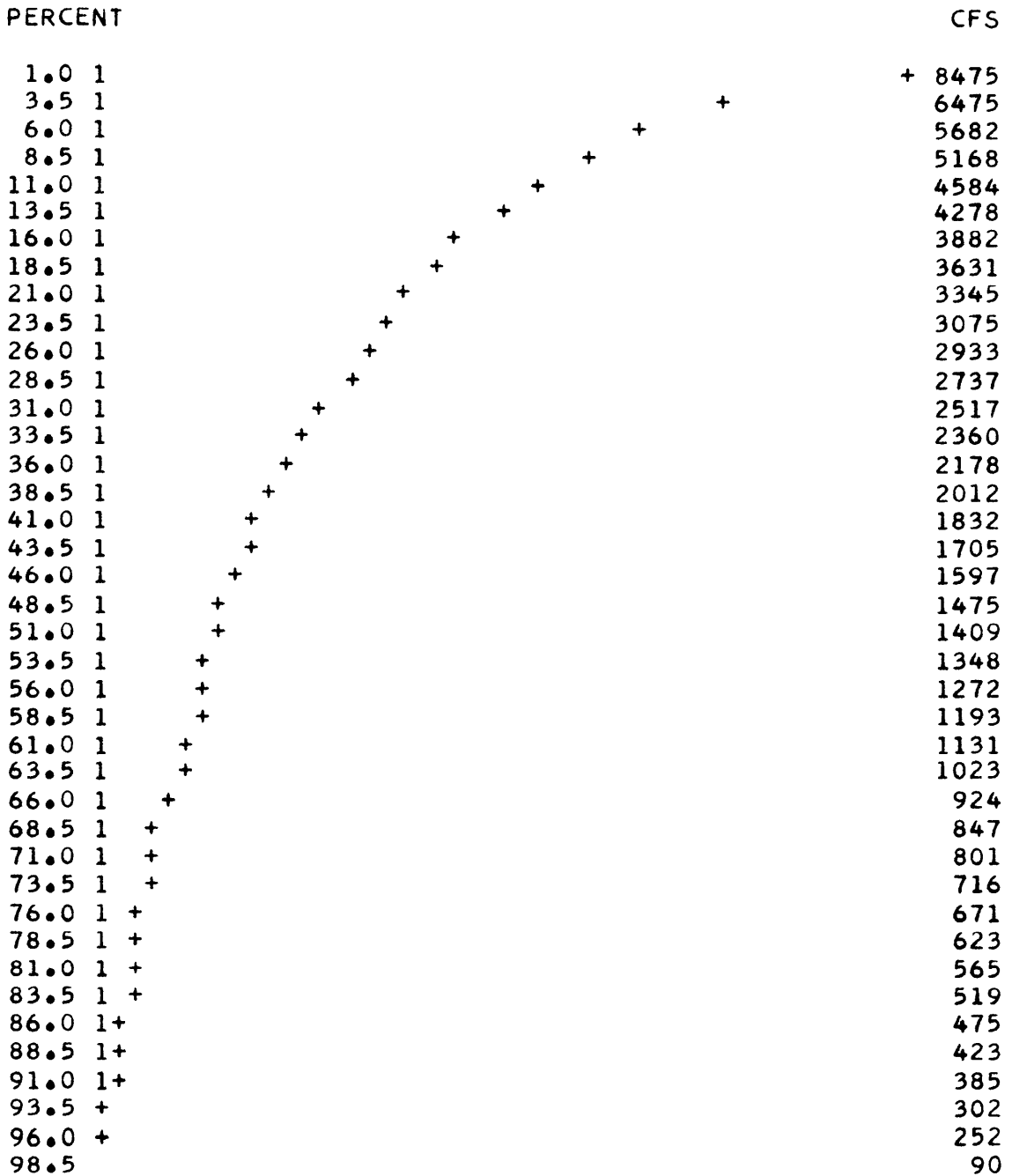


FIGURE 8. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON TYPE I DISTRIBUTION OF PRECIPITATION.

PERCENT		CFS
1.0	1	+ 7924
3.5	1	6409
6.0	1	5620
8.5	1	4939
11.0	1	4498
13.5	1	4081
16.0	1	3759
18.5	1	3536
21.0	1	3277
23.5	1	3010
26.0	1	2822
28.5	1	2621
31.0	1	2426
33.5	1	2248
36.0	1	2058
38.5	1	1934
41.0	1	1823
43.5	1	1673
46.0	1	1555
48.5	1	1465
51.0	1	1382
53.5	1	1331
56.0	1	1266
58.5	1	1192
61.0	1	1127
63.5	1	1059
66.0	1	988
68.5	1	912
71.0	1	836
73.5	1	781
76.0	1	734
78.5	1	684
81.0	1	639
83.5	1	578
86.0	1	502
88.5	1+	433
91.0	1+	406
93.5	+	314
96.0	+	261
98.5		106

FIGURE 9. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON TYPE I DISTRIBUTION OF PRECIPITATION.

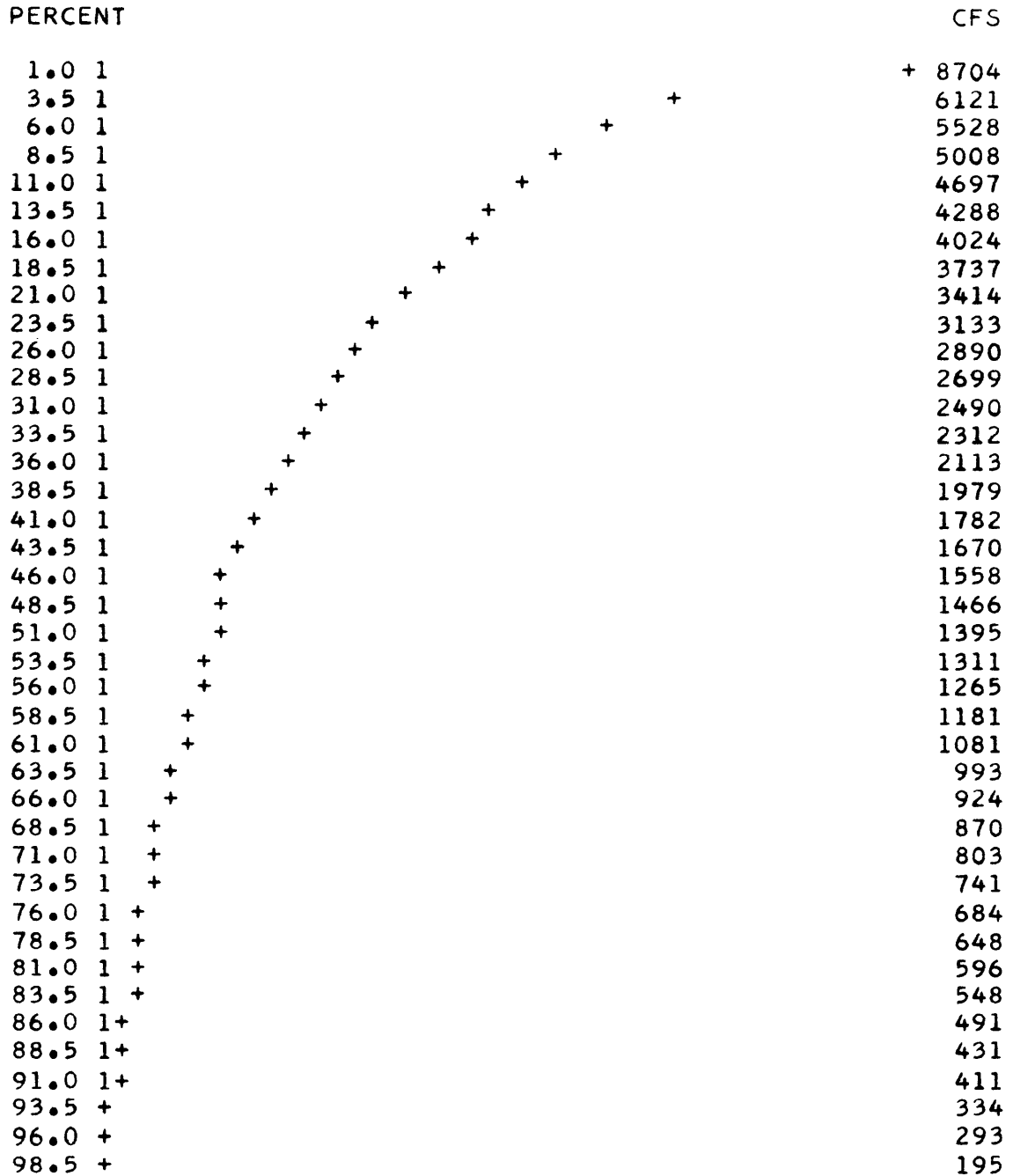


FIGURE 10. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON NORMAL DISTRIBUTION OF PRECIPITATION.

PERCENT		CFS
1.0	1	+ 7760
3.5	1	6188
6.0	1	5454
8.5	1	5019
11.0	1	4689
13.5	1	4281
16.0	1	3947
18.5	1	3657
21.0	1	3409
23.5	1	3214
26.0	1	2934
28.5	1	2674
31.0	1	2514
33.5	1	2336
36.0	1	2153
38.5	1	1983
41.0	1	1812
43.5	1	1697
46.0	1	1580
48.5	1	1505
51.0	1	1432
53.5	1	1378
56.0	1	1294
58.5	1	1242
61.0	1	1163
63.5	1	1108
66.0	1	1021
68.5	1	944
71.0	1	877
73.5	1	829
76.0	1	767
78.5	1	716
81.0	1	679
83.5	1	609
86.0	1	539
88.5	1	487
91.0	1+	412
93.5	+	302
96.0	+	293
98.5		109

FIGURE 11. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON NORMAL DISTRIBUTION OF PRECIPITATION.

PERCENT	CFS
1.0	7980
3.5	6146
6.0	5488
8.5	5084
11.0	4699
13.5	4375
16.0	4084
18.5	3814
21.0	3516
23.5	3200
26.0	2936
28.5	2743
31.0	2620
33.5	2379
36.0	2181
38.5	2010
41.0	1830
43.5	1730
46.0	1657
48.5	1556
51.0	1467
53.5	1403
56.0	1335
58.5	1252
61.0	1200
63.5	1129
66.0	1051
68.5	975
71.0	917
73.5	841
76.0	791
78.5	736
81.0	684
83.5	623
86.0	582
88.5	522
91.0	441
93.5	398
96.0	302
98.5	167

FIGURE 12. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON NORMAL DISTRIBUTION OF PRECIPITATION.

PERCENT	CFS
1.0	7999
3.5	6296
6.0	5512
8.5	5063
11.0	4668
13.5	4202
16.0	3909
18.5	3711
21.0	3492
23.5	3147
26.0	2984
28.5	2810
31.0	2638
33.5	2378
36.0	2209
38.5	2029
41.0	1928
43.5	1799
46.0	1723
48.5	1629
51.0	1510
53.5	1427
56.0	1373
58.5	1273
61.0	1193
63.5	1126
66.0	1028
68.5	921
71.0	849
73.5	784
76.0	723
78.5	684
81.0	640
83.5	581
86.0	522
88.5	455
91.0	410
93.5	335
96.0	293
98.5	144

FIGURE 13. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON NORMAL DISTRIBUTION OF PRECIPITATION.

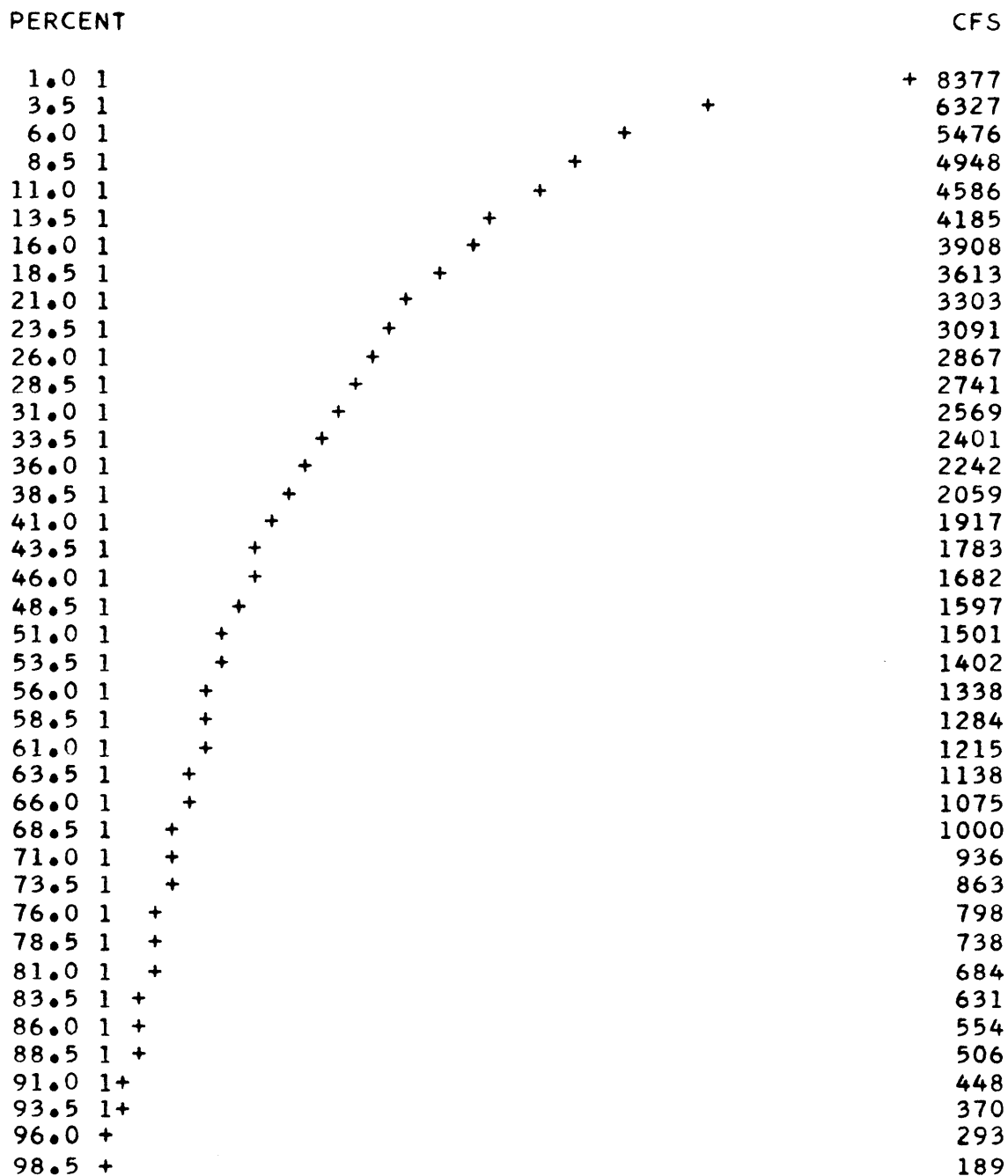


FIGURE 14. SAMPLE 100 YEAR FLOW DURATION CURVE FOR THE SYNTHETIC FLOWS OBTAINED THROUGH THE USE OF THE PEARSON NORMAL DISTRIBUTION OF PRECIPITATION.

PERCENT		CFS
1.0	1	+ 7831
3.5	1	5968
6.0	1	5492
8.5	1	4995
11.0	1	4681
13.5	1	4383
16.0	1	4082
18.5	1	3827
21.0	1	3490
23.5	1	3256
26.0	1	2991
28.5	1	2768
31.0	1	2586
33.5	1	2408
36.0	1	2209
38.5	1	2038
41.0	1	1891
43.5	1	1793
46.0	1	1696
48.5	1	1585
51.0	1	1501
53.5	1	1413
56.0	1	1361
58.5	1	1284
61.0	1	1200
63.5	1	1121
66.0	1	1041
68.5	1	959
71.0	1	865
73.5	1	810
76.0	1	711
78.5	1	684
81.0	1	644
83.5	1	591
86.0	1	541
88.5	1	488
91.0	1+	426
93.5	1+	370
96.0	+	302
98.5	+	278

Table 8. Dependable flows for synthetic records obtained through the use of the Pearson Type I distribution of precipitation.

5	10	Reservoir Size				30	35	40
		15	20	25				
822	1012	1203	1392	1478	1565	1651	1738	
768	1039	1311	1583	1855	1886	1897	1908	
970	1350	1691	1799	1854	1903	1952	1981	
934	1310	1420	1519	1589	1660	1730	1800	
646	868	1031	1117	1204	1290	1376	1463	
816	1054	1292	1530	1656	1702	1747	1792	
957	1260	1498	1735	1877	1920	1935	1944	
556	828	1100	1372	1594	1648	1672	1696	
613	851	1088	1326	1562	1648	1735	1821	
921	1321	1440	1535	1630	1725	1820	1910	
995	1304	1410	1516	1621	1727	1833	1874	
840	1168	1267	1329	1390	1451	1513	1574	
542	753	964	1176	1386	1502	1614	1721	
789	1007	1218	1418	1608	1657	1691	1724	
897	1278	1658	1782	1800	1815	1830	1845	
849	1087	1325	1560	1622	1683	1719	1749	
797	1142	1356	1461	1567	1673	1778	1838	
671	849	944	1040	1125	1191	1256	1322	
859	1176	1493	1810	1850	1867	1883	1900	
878	1116	1330	1425	1521	1603	1649	1696	
1002	1240	1478	1715	1807	1850	1887	1920	
1065	1382	1699	1765	1822	1880	1926	1943	
855	1127	1377	1477	1577	1673	1736	1797	
483	720	958	1196	1434	1672	1717	1730	
725	1042	1264	1359	1448	1511	1574	1626	

continued on next page

Table 8 continued

5	10	15	Reservoir Size		30	35	40
			20	25			
821	1071	1309	1415	1474	1534	1593	1653
971	1224	1329	1429	1493	1556	1619	1655
1093	1557	1850	1858	1866	1874	1882	1891
855	1045	1235	1426	1606	1666	1725	1759
680	918	1048	1144	1239	1334	1429	1524
913	1185	1456	1597	1656	1716	1775	1834
831	1120	1270	1365	1460	1555	1650	1745
716	981	1212	1423	1610	1674	1737	1801
790	1028	1266	1364	1393	1422	1451	1479
671	905	1010	1110	1210	1310	1410	1510
900	1091	1281	1471	1661	1775	1785	1795
639	892	1130	1368	1579	1750	1797	1843
941	1308	1580	1698	1759	1821	1868	1892
621	852	1042	1232	1329	1373	1417	1462
702	974	1085	1191	1297	1371	1416	1462
684	1002	1218	1330	1442	1543	1644	1729
777	1072	1326	1499	1574	1635	1697	1758
879	1116	1351	1562	1724	1756	1789	1822
586	858	1068	1174	1280	1385	1431	1476
829	1116	1228	1340	1452	1564	1676	1788
657	1037	1319	1383	1447	1510	1573	1637
629	939	1177	1398	1506	1612	1690	1732
721	943	1134	1324	1484	1546	1607	1669
847	1118	1366	1563	1753	1855	1867	1878
514	772	1009	1247	1485	1633	1679	1725

Reservoir size in billions of cubic feet
Dependable flow in cfs

Table 9. Dependable flows for synthetic records obtained through the use of the Pearson Normal distribution of precipitation.

	Reservoir Size						
	5	10	15	20	25	30	35
898	1264	1351	1437	1524	1610	1697	1783
753	943	1133	1324	1514	1704	1781	1822
1177	1511	1810	1874	1937	1988	2037	2050
1065	1259	1354	1436	1506	1577	1647	1718
793	1031	1237	1332	1427	1522	1618	1713
717	954	1192	1430	1668	1850	1896	1913
885	1230	1468	1706	1936	2053	2063	2072
685	957	1229	1500	1557	1606	1654	1703
766	1044	1281	1415	1501	1588	1674	1761
775	1026	1237	1449	1599	1695	1790	1845
1004	1321	1451	1557	1663	1768	1874	1925
874	1349	1464	1526	1587	1649	1706	1750
729	1026	1298	1553	1672	1786	1844	1853
932	1204	1416	1554	1612	1645	1678	1712
898	1278	1641	1777	1876	1891	1906	1921
899	1170	1442	1688	1771	1802	1832	1862
970	1351	1537	1643	1748	1849	1859	1870
783	939	1034	1130	1215	1281	1347	1412
1009	1279	1481	1531	1577	1622	1667	1713
895	1140	1378	1615	1738	1844	1950	2006
831	1149	1272	1384	1496	1608	1717	1822
1276	1673	1825	1881	1937	1993	2016	2030
878	1167	1439	1686	1787	1880	1893	1906
902	1174	1445	1583	1689	1755	1812	1833
961	1074	1186	1298	1410	1522	1633	1722

continued on next page

Table 9 continued

5	10	Reservoir Size				30	35	40
		15	20	25				
786	1024	1262	1433	1528	1580	1626	1671	
880	1152	1407	1534	1563	1591	1620	1648	
1242	1689	1883	1957	1964	1972	1980	1988	
1170	1319	1431	1543	1623	1683	1742	1801	
666	904	1139	1234	1329	1424	1519	1603	
1063	1348	1620	1713	1775	1836	1897	1959	
1036	1260	1347	1433	1520	1606	1693	1779	
866	1236	1554	1658	1721	1785	1848	1912	
702	940	1153	1364	1576	1684	1705	1726	
780	970	1160	1292	1392	1492	1592	1688	
521	712	902	1092	1282	1473	1663	1692	
1001	1290	1527	1690	1756	1810	1859	1905	
958	1165	1356	1546	1736	1769	1794	1818	
907	1263	1390	1517	1644	1716	1768	1821	
857	1065	1177	1288	1396	1480	1526	1571	
904	1094	1260	1372	1484	1596	1701	1802	
853	1125	1397	1577	1622	1666	1710	1754	
605	843	1081	1211	1306	1401	1496	1591	
707	945	1182	1420	1658	1734	1779	1824	
696	1014	1223	1350	1471	1583	1695	1807	
744	1064	1368	1468	1535	1577	1620	1662	
710	1027	1344	1533	1639	1744	1850	1857	
984	1176	1366	1475	1575	1676	1776	1843	
943	1214	1469	1680	1832	1842	1851	1861	
742	978	1168	1359	1549	1691	1725	1759	

Reservoir size in billions of cubic feet
Dependable flow in cfs

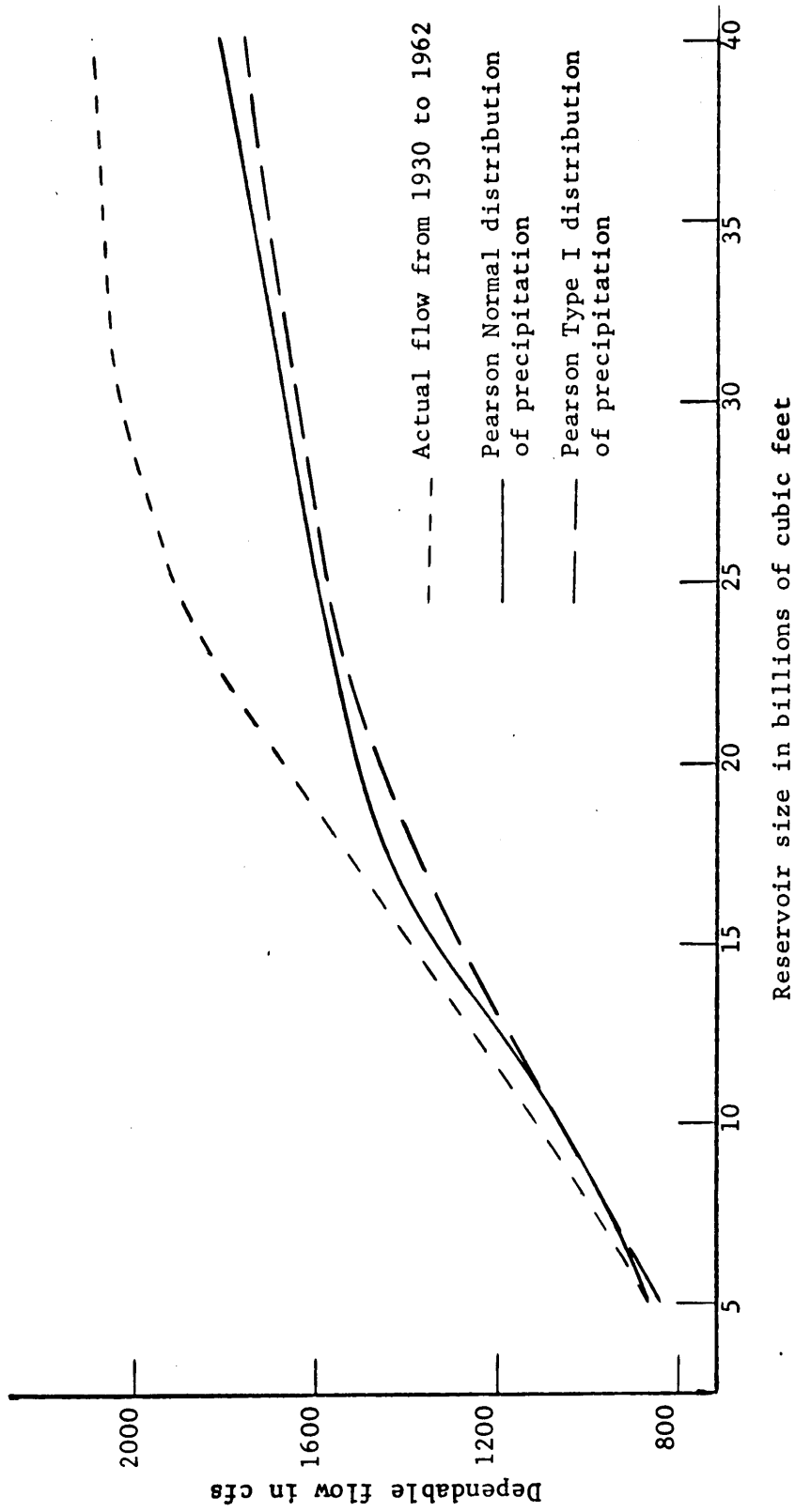
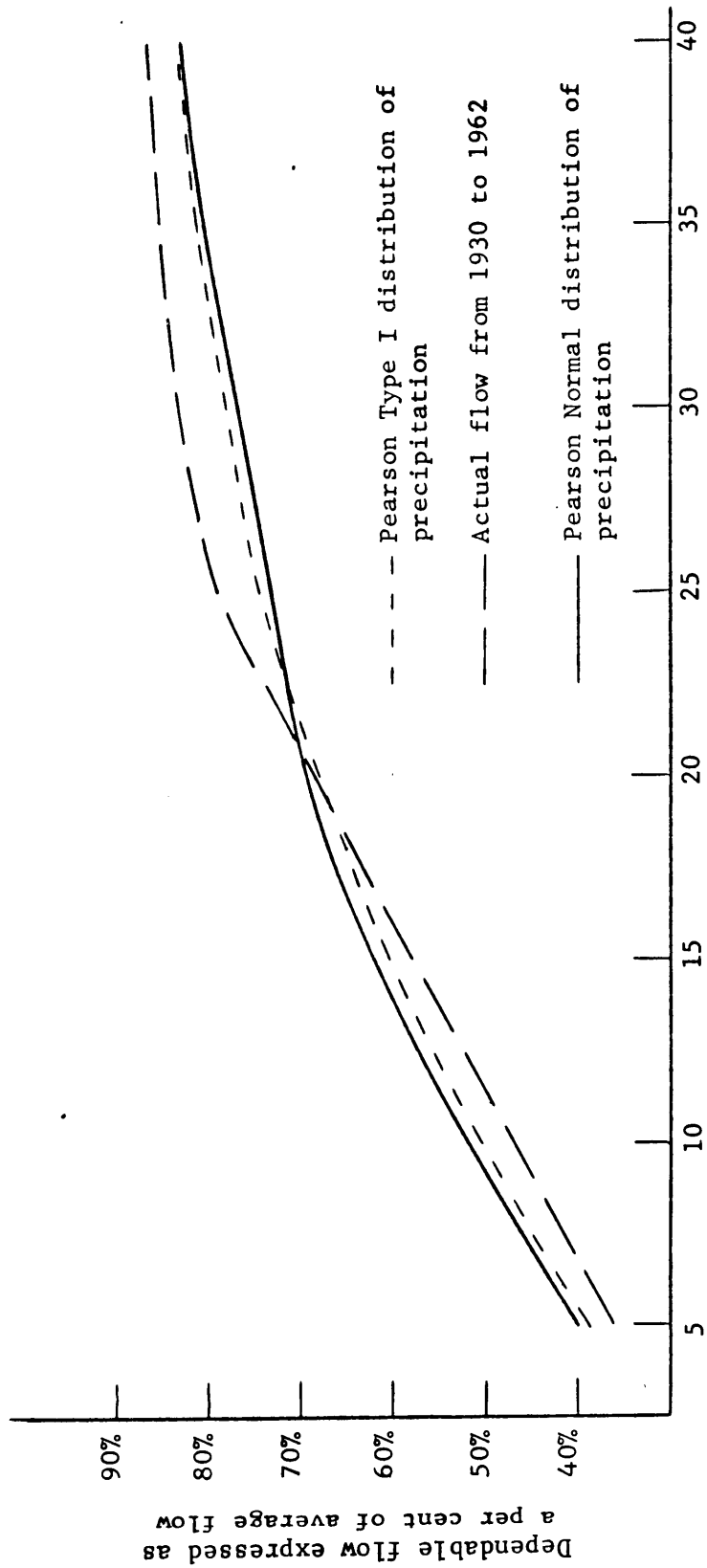


Figure 15. Mean dependable flows for both synthetic models compared with the actual dependable flow for the period 1930 to 1962 for the James River at Buchanan, Virginia.



Reservoir size in billions of cubic feet

Figure 16. Mean dependable flows, expressed as a per cent of the average flow, for both synthetic series compared with the dependable flow for the period 1930 to 1962, expressed as a per cent of the average flow, for the James River at Buchanan, Virginia.

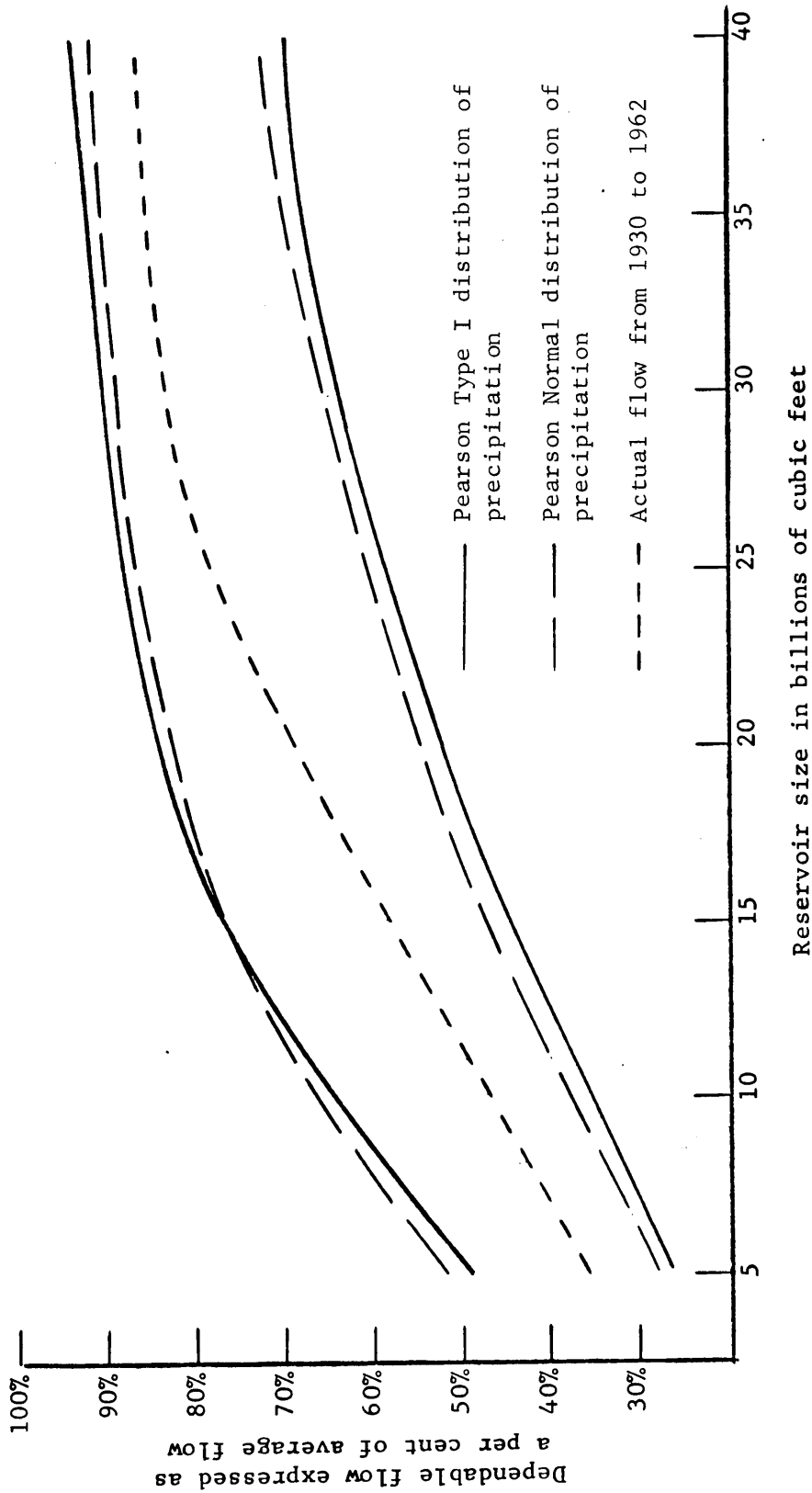


Figure 17. Ninety per cent confidence limits on the dependable flows, expressed as a per cent of the average flow for both synthetic flow models.

DISCUSSION OF RESULTS

This investigation was conducted in order to construct a synthetic hydrologic model for the James River flow at Buchanan, Virginia. The simulation of streamflows is important in reducing some of the deficiencies in water resource studies preliminary to planning, design, and operation. The application of simulated flows adds considerably to the amount of computation involved in such studies. Through the use of digital computers, extensive computation does not constitute a serious problem.

The initial model for each month contained the four previous recorded monthly flows and the four most recent monthly precipitation totals. It was discovered that the mean monthly flow and precipitation of more than a month previous did not add significantly to the over-all correlation coefficient for the monthly model. This led to the assumption that the monthly mean flow was serially correlated to only the previous month's hydrologic parameters. Various functions and cross-products were then introduced and applied only to the precipitation of the month in question, and the previous months precipitation and flow. It was of interest to note that within successive months, the same functions were usually very significant.

The "Pearson Universal Random Number Generator", (PURGE) has some special characteristics that merit attention. The Pearson Types I, III, IV and the Pearson Normal curves, as well as subtypes of them, may be fitted to point data (36). If raw point data are given, the PURGE subroutine determines the appropriate Pearson type, using moments calculated from the data.

The Pearson Type I distributor was selected as the appropriate distribution for all twelve of the monthly precipitations. The Pearson Type I distribution is a representative of the beta distribution. It appeared that the beta distribution was an applicable distribution for the monthly precipitation studied.

An additional option of "PURGE" allows all but Type III to be force fitted. The monthly precipitation data was force-fitted to a Pearson Normal distribution to determine if more than one distribution could describe the monthly precipitation. Some of the random precipitations from the Pearson Normal distribution were negative. These values were not changed when they were used to generate the synthetic flows.

The artificial monthly precipitations from both distributions seem to be equally representative of the monthly precipitation totals with the exception of the negative values given by the Pearson Normal distribution. All four moments from the artificial precipitation from both distributions agree with the actual data moments to the closest hundredth. The Pearson Normal distribution generator gave larger positive values of monthly rainfall than did the Pearson Type I distribution generator, in order to correct the mean for the negative values.

The 5000-year average synthetic mean monthly flow generated through the use of the Pearson Type I distribution of precipitation was 2110 cfs. The 5000-year average synthetic mean monthly flow generated through the use of the Pearson Normal distribution of precipitation was 2179 cfs.

Both sequences of 5000 years of synthetic flows were biased negatively as the average mean monthly flow for the thirty-two years used in construction of the model was 2439 cfs. The average synthetic flow utilizing the Pearson Type I distribution of rainfall was 86 per cent of the thirty-two year average, and the synthetic flow utilizing the Pearson Normal distribution of monthly precipitation was 89 per cent of the thirty-two year average.

Part of the bias may have stemmed from a lack of rainfall information. As in all types of measurement procedures, the measurement of rainfall is subject to various errors. Instrument errors are usually small if the instrument is kept in good order. Observer errors are usually small and self-compensating. Environmental changes around a precipitation station might be slowly introduced, such as the influence of the growth of a nearby tree, or might be rapidly introduced by the construction of a building within the vicinity of the gage. When there was no rainfall in the upper James River basin, all of the six precipitation stations recorded the fact. However, it is impossible to ascertain how often a significant amount of rain fell in the basin which was not accurately represented at the precipitation stations. The areal distribution of rainfall is by no means uniform for any given storm, and it is not consistent from storm to storm. Pronounced areal variation of rainfall can be found over areas as small as a few square miles. Thunderstorms, for example, characteristically show high concentrations of rainfall over small areas. More widely dispersed rains can also show considerable

variation between adjacent areas. There are many instances in the precipitation-flow data, where large mean monthly flows are unexplainable in terms of the actual precipitation record. A large rainfall could have missed a majority of precipitation stations and yet have had a profound effect on the flow at Buchanan, Virginia. Therefore, the monthly models, which were fitted by a least-squares approach, did not incorporate the unexplainable flows, in terms of the precipitation values.

This bias affects the absolute magnitude of the dependable flow for the larger reservoir sizes, as the dependable flow approaches the average flow asymptotically. It appears that the effect of bias is alleviated when the dependable flow for a reservoir size is expressed as a per cent of the average flow for the series in question which is the 100-year record of mean monthly flow.

In Figure 16, page 53, the median dependable flow, expressed as a per cent of the average flow, for both synthetic series compares favorably with the dependable flow of the actual thirty-two year record. A comparison of the flow duration curves show that the synthetic flows are very representative of the actual flows. The magnitude of the synthetic flows are slightly smaller than the actual flows, however. The dependable flows of the thirty-two year record is always within ten per cent of the mean dependable flow forecast by the synthetic hydrologic model for a specified reservoir size.

In Figure 17, page 54, 90 per cent confidence intervals were placed on the dependable flow for both types of synthetic flows. It is interesting to note the wide range of possible dependable flows for a specified reservoir size. Both the Pearson Type I and Pearson Normal distributions of rainfall give approximately the same 90 per cent confidence interval. It appears that this representation of the possible dependable flow variability is reasonably accurate. The variability was caused by the dependence of the dependable flow on the sequence of monthly flows, more than on the average flow for the period in question. The 90 per cent confidence intervals become smaller as the dependable flows begin to asymptotically approach the average flow.

A comparison of the two 5000-year synthetic flows shows that both the Pearson Normal and Pearson Type I distribution are equally applicable from the standpoint of the values of the synthetic flows. The Pearson Normal distribution has the disadvantage that it is not bounded by zero as the lower limit which causes it to produce negative rainfalls. The Pearson Normal distribution does give somewhat narrower confidence limits than does the Pearson Type I distribution.

The synthetic dependable flows, expressed as a percentage of the mean, appear to be representative of the variability and magnitude of the possible dependable flows. A synthetic flow record adds to the knowledge of the James River based solely on the past historical record. The design of a regulation structure on the James River at Buchanan, Virginia should be more applicable if the designer is

aware of the various possibilities of future flow conditions. Representative future flow conditions were generated through the use of a synthetic hydrologic model.

CONCLUSIONS

The following conclusions may be drawn from this investigation.

1. The monthly mean flow of the James River at Buchanan, Virginia is serially correlated to the precipitation of the month in question and the previous months' precipitation and mean flow. Hydrologic parameters beyond one previous month are usually insignificant.
2. Fitting monthly models to the flow and precipitation data by the Stepwise Regression method is applicable. The average correlation coefficient of 0.77 is considered good.
3. The Pearson Type I distribution is very representative of the total monthly precipitation for the upper James River Basin.
4. All of the output of the synthetic hydrologic model described in this thesis can be expected to incorporate the errors of the original record of precipitation and flow.
5. The magnitude of the synthetic flows obtained from the Pearson Type I and Pearson Normal distribution of precipitation are approximately the same.
6. It appears that a synthetic hydrologic model of the type described is applicable to the simulation of the mean monthly flow of the James River at Buchanan, Virginia.
7. The dependable flow, expressed as a percentage of the average flow for the period in question, does have a wide range of variability.

8. The past historic record of the James River at Buchanan, Virginia is as representative of future conditions as is any other single record. A reservoir size selected only on the basis of the past historic flow of the James River at Buchanan, Virginia would be meaningful.

SUMMARY

For engineering-economic analysis of a river system, an estimate of future flow conditions or flows of a river is needed in order to achieve the ultimate design of any river basin project. The problem becomes one of finding a method or technique of generating artificial flows which are characteristic of the river in question.

The object of this thesis is the synthetic generation of possible future flows in the James River at Buchanan, Virginia, through the utilization of existing records of monthly precipitation and runoff. Twelve separate monthly regression models were chosen on the basis of the degree of correlation as indicated by the correlation coefficient. Random monthly precipitation totals were generated from the twelve separate distributions of historical monthly precipitation totals. The synthetic precipitations were used in the twelve monthly models to generate 5000-years of artificial record.

The 5000-year synthetic record was divided into fifty separate 100-year records for the purpose of analysis. The dependable flows were found for each of the fifty records for each of eight reservoir sizes. The ninety per cent confidence interval and the dependable flow for each of eight reservoir sizes was found.

The model had a negative bias of approximately thirteen per cent. This bias appeared to be alleviated when the dependable flow was expressed as a per cent of the average flow for the period in question.

It appears that there is great variability in the estimated value of the dependable flow in the James River.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Dr. William A. Parsons, Dr. James M. Wiggert, and Dr. Raymond H. Myers for their valuable suggestions and ideas.

The author would also like to thank _____ for his constructive criticism and guidance.

The author also thanks _____ for her excellent typing of this thesis.

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APPENDIX. IBM 7040 COMPUTER PROGRAM FOR THE
 GENERATION OF SYNTHETIC FLOW FOR THE JAMES RIVER
 AT BUCHANAN,VIRGINIA.

```

C   CUMDP(I)=CUMULATIVE DEPARTURE FROM AVERAGE
C   AVG=AVERAGE FLOW FOR 100 YEARS
C   FLO(J,I)=MONTHLY MEAN FLOW
C   PREP(J,I)=MONTHLY PRECIPITATION TOTAL
C   RDS(N)=RANDOM NUMBER FROM DISTRIBUTION OF PREVIOUS
C           ACTUAL TOTAL MONTHLY PRECIPITATION
DIMENSION FLOW(1200)
DIMENSION FLO(101,12),CUMDP(1201),SLOPE(1201),A(1201),
1PREP(100,12),GFLOW(50,16),WAST(50,16)
COMMON/Z2/RDS(100)
COMMON/VPI001/NUMBR
LIMIT=100
REWIND 0
DO 70 I=1,12
CALL PURGE2(1,1)
IF(LIMIT.EQ.0) GO TO 200
WRITE(0)RDS
DO 73 J=1,4
CALL PURGE2(2,1)
IF(LIMIT.EQ.0) GO TO 200
73 WRITE(0)RDS

```

```

CALL PURGE2(2,4)
IF (LIMIT.EQ.0) GO TO 200
PRINT 131,NUMBR
131 FORMAT(10X,8HNUMBR = ,I20)
70 CONTINUE
CALL  CHKPT(30)
REWIND 0
J6=0
DO 400 J5=1,5
CALL SUB(J5,PREP)
IF(J5-1)90,90,91
90 J=0
92 PRINT 93
PUNCH 93
93 FORMAT(1H1,22X,27HSAMPLE OF GENERATED MONTHLY,/,
125X,20HPRECIPIATION TOTALS,/)
PRINT 94
PUNCH 94
94 FORMAT(7X,34HJAN.      FEB.      MAR.      APR.,
16X,14HMAY      JUNE)
DO 95  JJ=1,20
J=J+1
95 PRINT 96,(PREP(J,I),I=1,6)
PUNCH 96,(PREP(J,I),I=1,6)
96 FORMAT(1X,6F10.2)

```

```

      IF(J-100)92,97,97
97 J=0
197 PRINT 93
      PUNCH 93
      PRINT 98
      PUNCH 98
98 FORMAT( 7X,34HJULY      AUG.      SEPT      OCT.,
16X,14HNOV.      DEC.)
      DO 570 K=1,20
      J=J+1
      PUNCH 96,(PREP(J,I),I=7,12)
570 PRINT 96,(PREP(J,I),I=7,12)
      IF(J-100) 197,91,91
91 DO 100 J=1,100
      DO 100 I=1,12
C      MONTHLY MODELS FOR MEAN MONTHLY FLOW OF JAMES RIVER
C      AT BUCHANAN VIRGINIA
      GO TO (111,112,113,114,115,116,117,118,119,120,121,122
1),I
111 IF(J-1) 110,110,74
110 FLO(J,I)=-.91291+2.1416*ALOG10( 2.3126  )+1.159*(PRE
1P(J,I))+.001*EXPF( 2.8400  )
      IF(FLO(J,I)-0.0) 221,221,100
74 FLO(J,I)=-.91291+2.1416*ALOG10(FLO(J-1,12))+1.159*(PRE
1P(J,I))+.001*EXPF(PREP(J-1,12))

```

```

      IF(FLO(J,I)-0.0) 221,221,100
112 IF(J-1)109,109,108
109 FLO(J,I)=-1.0798+6.1175*ALOG10(FLO(J,I-1))+1.622*PREP(
      1J,I)-.97263*FLO(J,I-1)+.43069* 2.3126  +.003296*EXPF
      2(PREP(J,I-1))
      IF(FLO(J,I)-0.0) 222,222,100
108 FLO(J,I)=-1.0798+6.1175*ALOG10(FLO(J,I-1))+1.622*PREP(
      1J,I)-.97263*FLO(J,I-1)+.43069*FLO(J-1,12)+.003296*EXPF
      2(PREP(J,I-1))
      IF(FLO(J,I)-0.0) 222,222,100
113 FLO(J,I)=-.95817+.10575*PREP(J,I)*PREP(J,2)+1.04*PREP(
      1J,I)+.19878*FLO(J,I-1)
      IF(FLO(J,I)-0.0) 232,232,100
114 FLO(J,I)=10.**(.24844+.1377*FLO(J,3)-.27127*PREP(J,3)-
      1.03848*PREP(J,3)*FLO(J,3)+.00025425*EXPF(PREP(J,3))+.4
      26765*ALOG10(PREP(J,I))+.075186*PREP(J,I)*PREP(J,3))
      IF(FLO(J,I)-0.0) 242,242,100
115 FLO(J,I)=-4.1086+1.2866*PREP(J,I)+.54844*FLO(J,I-1)+.5
      1244*PREP(J,I-1)-.03239*PREP(J,I)*FLO(J,I-1)*PREP(J,4)
      IF(FLO(J,I)-0.0) 252,252,100
116 FLO(J,I)=2.1483+.10817*PREP(J,I)*PREP(J,5)-.72993*PREP
      1(J,I)+.0095*EXPF(PREP(J,I))-0.002186*EXPF(PREP(J,5))
      IF(FLO(J,I)-0.0) 262,262,100
117 FLO(J,I)=10.**(-.26781-.14757*FLO(J,6)+.83278*ALOG10(F
      1LO(J,6))-0.00047137*EXPF(PREP(J,6))+.02698*PREP(J,I)*PR

```

```

2EP(J,6))
      IF(FLO(J,I)-0.0) 272,272,100
118 FLO(J,I)=-.81874+.43212*PREP(J,I)-.28365*PREP(J,7)+.54
      1227*FLO(J,6)+.005122*EXPF(PREP(J,7))
      IF(FLO(J,I)-0.0) 282,282,100
119 FLO(J,I)=.45978-.03433*PREP(J,I)*PREP(J,8)+.0104*(PREP
      1(J,I)**3.+.002705*(PREP(J,8)**3.)
      IF(FLO(J,I)-0.0) 292,292,100
120 FLO(J,I)=1.6448+3.8851*ALOG10(FLO(J,9))+.3092*PREP(J,I
      1)-1.5573*FLO(J,9)+.0017177*EXPF(PREP(J,9))+.3975*PREP(
      2J,I)*FLO(J,9)-.0702*PREP(J,I)*FLO(J,9)*PREP(J,9)
      IF(FLO(J,I)-0.0) 302,302,100
121 FLO(J,I)=10.**(-.21467+.78217*ALOG10(PREP(J,I))+.7002*
      1ALOG10(FLO(J,10))-0.0382*ALOG10(PREP(J,10)))
      IF(FLO(J,I)-0.0) 312,312,100
122 FLO(J,I)=10.**(-.19298+1.0191*ALOG10(PREP(J,I))+.7944*
      1ALOG10(FLO(J,11))-0.05722*ALOG10(PREP(J,11)))
      IF(FLO(J,I)-0.0) 322,322,100
C      CORRECTIONS FOR MINUS FLOW
C      MINUS FLOWS ARE SET EQUAL TO MINIMUM MEAN MONTHLY
C      FLOW ACTUALLY RECORDED
221 FLO(J,I)=.371
      GO TO 100
222 FLO(J,I)=.412
      GO TO 100

```

```
232 FLO(J,I)=1.779
      GO TO 100
242 FLO(J,I)=1.100
      GO TO 100
252 FLO(J,I)=.685
      GO TO 100
262 FLO(J,I)=.542
      GO TO 100
272 FLO(J,I)=.317
      GO TO 100
282 FLO(J,I)=.303
      GO TO 100
292 FLO(J,I)=.289
      GO TO 100
302 FLO(J,I)=.294
      GO TO 100
312 FLO(J,I)=.329
      GO TO 100
322 FLO(J,I)=.415
100 CONTINUE
      CALL  CHKPT(30)
C          PUNCH FLOWS
      DO 132 J=1,100
      DO 132 I=1,12
132 FLO(J,I)=1000.*FLO(J,I)
```

```
      IF(J6)80,80,136
80  J=0
331 PRINT 413
      PUNCH 413
413 FORMAT(1H1,17X,28H GENERATED MEAN MONTHLY FLOW,
      17H IN CFS,/)
      PUNCH 94
      PRINT 94
      DO 81 K=1,20
      J=J+1
      PUNCH 82,(FLO(J,I),I=1,6)
81  PRINT 82,(FLO(J,I),I=1,6)
82  FORMAT(2X,6F10.0 )
      IF(J-100)331,83,83
83  J=0
84  PRINT 413
      PUNCH 413
      PRINT 98
      PUNCH 98
      DO 85 K=1,20
      J=J+1
85  PRINT 82,(FLO(J,I),I=7,12)
      PUNCH 82,(FLO(J,I),I=7,12)
      IF(J-100) 84,136,136
136 N=0
```

```

DO 71 J=1,100
DO 71 I=1,12
N=N+1
71 FLOW(N)=.002628*FLO(J,I)
IF(J6)137,137,138
137 READ(5,101) N,A1,A2,A3,(A(I),I=1,12),NYEAR
101 FORMAT (I4,3A1,12A4,I5)
N6=N
138 SUMF=0.0
N=N6
DO 2 I=1,N
2 SUMF = SUMF + FLOW(I)
X=N
AVG = SUMF/X
AVER=AVG/.002628
GO TO 140
C CUMULATIVE MASS DIAGRAM
139 CUMDP(1)=FLOW(1)-AVG
DO 4 I=2,N
4 CUMDP(I) = CUMDP(I-1) + FLOW(I) - AVG
C CUMULATIVE DEPARTURE FROM NORMAL IN BILLIONS OF
C CUBIC FEET PER MONTH
DO 126 I=13,N
J=I-12*(I/12)
IF(J) 125,125,126

```

```

125 J=12
126 A(I)=A(J)
      WRITE(6,102)
      PUNCH 102
102 FORMAT(30X,40H CUMULATIVE DEPARTURE FROM NORMAL IN BIL,
125HLIONS OF CUBIC FEET/MONTH,/)
      CALL PLOT1 (CUMDP,A,NYEAR,N,A1,A2,A3)
C   MASS CURVE OF UNREGULATED STREAM FLOW
140 RES = 5.
      L3=0
      CUMDP(1) = FLOW(1)
      DO 10 I=2,N
10  CUMDP(I)=FLOW(I)+ CUMDP(I-1)
      PRINT 103
      PUNCH 103
103 FORMAT(1H1,/,18X,29HANALYSIS FOR TYPICAL 100 YEAR,
15H FLOW,/,9X,18HRESERVOIR CAPACITY,4X,11HDEPENDABLE ,
24HFLOW,4X,11HTOTAL WASTE,/,11X,13HBILLION FT**3,13X,
33HCFS, 9X,13HBILLION FT**3,/)
6  M=0
      L3=L3+1
      I=0
21  I=I+1
      IF (FLOW(I)-AVG) 23,22,22
22  IF(I-N) 21,24,24

```

```
23 IF (I-N) 25,24,24
25 K=0
    II=I+1
26 K=K+1
    Q=K
    IF (II-N) 27,28,28
27 AVGK = AVG*Q+ CUMDP(I)
    IF (CUMDP(II)-AVGK) 20,28,28
20 II=II+1
    GO TO 26
28 J=I+1
29 M=M+1
    X=J-I
    SLOPE(M)=(CUMDP(J)+RES-CUMDP(I))/X
    J10=J+1
    IF (II-J10)31,31,30
30 J= J+1
    GO TO 29
31 I =II
    GO TO 21
24 DEPFL = SLOPE(1)
    MM =1
32 MM = MM+1
    IF (MM-M) 33,33,34
33 IF (DEPFL-SLOPE(MM)) 32,35,35
```

```

35 DEPFL = SLOPE(MM)
   GO TO 32

34 X=N6

   WASTE=(AVG-DEPFL)*X
   GFLOW(J5,L3)=DEPFL/.002628
   WAST(J5,L3)=WASTE

   PRINT 105,RES,GFLOW(J5,L3),WASTE
   PUNCH 105,RES,GFLOW(J5,L3),WASTE
105 FORMAT (13X,F6.0,12X,F10.0,5X,F9.0)

   RES=RES+5.
   IF(RES-40.)6,6,36

36 PRINT 37,AVER
   PUNCH 37,AVER

37 FORMAT(//,23X,15HAVERAGE FLOW = ,F7.0,3HCFS)
C   DURATION DATA OF UNREGULATED STREAM FLOW

   I=1

59 DO 60 J=I,N
   IF(FLOW(I)-FLOW(J))61,60,60

61 X=FLOW(I)
   FLOW(I) = FLOW(J)
   FLOW(J)= X

60 CONTINUE

   I=I+1

   IF(I-N)59,59,55

55 CONTINUE

```

```
      CALL PLOT2 (FLOW,N,A1,A2,A3)
400  J6=J6+100
      I=1
      K=5
155  PRINT 153,(J=1,8)
      PUNCH 153,(J=1,8)
153  FORMAT(1H1,/,/,22X,26HDEPENDABLE FLOW IN CFS FOR,
           1/,18X,34HDIFFERENT 100 YEAR GENERATED FLOWS,/,
           220X,40HRESERVOIR SIZE IN BILLIONS OF CUBIC FEET,
           3/,24X,22HDEPENDABLE FLOW IN CFS,/,/,6X,4HSIZE,3X,
           48(4HRUN ,I1,2X))
165  PRINT 154,K,(GFLOW(J,I),J=1,8)
      PUNCH 154,K,(GFLOW(J,I),J=1,8)
154  FORMAT(7X,I2,1X,8F7.0)
      K=K+5
      I=I+1
      IF(K-40) 165,165,54
54   CALL EXIT
200  STOP
      END
$IBFTC D2
C                                     FUNCTION PLOTTER
C
      SUBROUTINE   PLOT1(X,A,NYEAR,NOPTS,A1,A2,A3)
C
```

```
DIMENSION X(300),PLPOS(101),A(300)
```

```
C
```

```
WRITE (6,101)
```

```
101 FORMAT (13H YEAR MONTH,113X,4HFLOW/)
```

```
XMAX=ABS(X(1))
```

```
DO 2 I=2,NOPTS
```

```
XCHK=ABS(X(I))
```

```
IF (XMAX-XCHK) 1,2,2
```

```
1 XMAX=XCHK
```

```
2 CONTINUE
```

```
DO 3 J=1,101
```

```
3 PLPOS(J) = A1
```

```
DO 5 I=1,NOPTS
```

```
N=(X(I)*50.)/XMAX+51.5
```

```
PLPOS(51)=A2
```

```
PLPOS(N)=A3
```

```
IF (A(I)-A(1)) 31,32,31
```

```
32 WRITE (6,103) NYEAR,A(I),(PLPOS(J), J=1,101),X(I)
```

```
103 FORMAT (15,3X,A4,3X,101A1,F14.2)
```

```
NYEAR=NYEAR+1
```

```
GO TO 5
```

```
31 WRITE (6,102) A(I),(PLPOS(J), J=1,101),X(I)
```

```
102 FORMAT (8X,A4,3X,101A1,F14.2)
```

```
5 PLPOS(N)=A1
```

```
RETURN
```

```
END
$IBFTC D3
C
SUBROUTINE PLOT2 (X,N,A1,A2,A3)
DIMENSION X(1200),PLPOS(51)
PRINT 101
101 FORMAT(1H1,22X,26HSAMPLE FLOW DURATION CURVE,/,
15X,7HPERCENT,49X,3HCFS)
DO 1 J=2,50
1 PLPOS(J)=A1
PLPOS(1) = A2
DO 2 I=12,1182,30
L=(50.*X(I))/X(1)+(50.*(X(1)-X(12))/X(1))
PLPOS(L)=A3
Y1=I
Y2=N
K=X(I)/.002628
Y=(100.*Y1)/Y2
PRINT 103,Y,(PLPOS(J),J=1,51),K
PUNCH 103,Y,(PLPOS(J),J=1,51),K
103 FORMAT(5X,F4.1,1X,50A1,14)
2 PLPOS(L) = A1
RETURN
END
$IBFTC D4
```

C

```
SUBROUTINE SUB(NO,PREP)
DIMENSION PREP(100,12),TEMP(100)
REWIND 0
DO 10 I=1,12
DO 10 J=1,5
IF(J.EQ. NO)GO TO 5
READ (0) TEMP
GO TO 10
5 READ (0)(PREP(K,I),K=1,100)
10 CONTINUE
REWIND 0
RETURN
END
```

A SYNTHETIC HYDROLOGIC FLOW MODEL FOR
THE UPPER JAMES RIVER BASIN

by

NEWTON VAUGHAN COLSTON, JR.

ABSTRACT

The object of this thesis is the synthetic generation of possible future flows in the James River at Buchanan, Virginia, through the utilization of existing records of monthly precipitation and runoff. Twelve separate monthly regression models were chosen on the basis of the degree of correlation as indicated by the correlation coefficient. Random monthly precipitation totals were generated from the twelve separate distributions of historical monthly precipitation totals. The synthetic precipitations were used in the twelve monthly models to generate 5000-years of artificial record.

The 5000-year synthetic record was divided into fifty separate 100-year records for the purpose of analysis. The dependable flows were found for each of the fifty records for each of eight reservoir sizes. The ninety per cent confidence interval and the dependable flow for each of eight reservoir sizes was found.

The model had a negative bias of approximately thirteen per cent. This bias appeared to be alleviated when the dependable flow was expressed as a per cent of the average flow for the period in question. It appears that there is great variability in the estimated value of the dependable flow in the James River.