Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter B2

STORAGE ANALYSES FOR WATER SUPPLY

By H. C. Riggs and Clayton H. Hardison

Book 4

HYDROLOGIC ANALYSIS AND INTERPRETATION

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

Reprinted 1983

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1983

For sale by the Distribution Branch, U.S. Geological Survey
604 South Pickett Street, Alexandria, VA 22304

PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called books and further subdivided into sections and chapters; Section B of Book 4 is on surface water.

The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises.

Provisional drafts of chapters are distributed to field offices of the U.S. Geological Survey for their use. These drafts are subject to revision because of experience in use or because of advancement in knowledge, techniques, or equipment. After the technique described in a chapter is sufficiently developed, the chapter is published and is for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

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STORAGE ANALYSES FOR WATER SUPPLY

By H. C. Riggs and Clayton H. Hardison

Abstract

This manual briefly describes various methods of storage analysis and recommends one method for use by the U.S. Geological Survey to produce draft-storage relations useful to planners and designers. The recommended method is described in detail.

Introduction

Demands for water supplied by a stream are often greater than minimum streamflow, but these demands can be met by providing storage. The design of a storage project should consider the streamflow characteristics, the magnitude and variability of draft, the physical characteristics of the storage site, the economic consequences of a temporary deficiency in draft, the effect of reservoir evaporation, the probable reduction in reservoir capacity because of sedimentation, and the need to serve other purposes such as flood control or conservation pool storage, or to permit a restricted range in water level for recreation.

A responsibility of the U.S. Geological Survey is to furnish hydrologic information for use in reservoir design. This manual describes and discusses current and traditional methods of analysis of storage to augment low flows. One method that will produce results useful to planners and designers is recommended for use by the Geological Survey.

Recent trends in analysis of the storage required to furnish given draft rates have emphasized the assignment of a probability of failure to maintain the given draft with computed storage. Storage requirements depend on the sequence of events as well as on the magnitudes of those events. Thus an estimate of probability based only on one sequence (the record) is of limited reliability. The methods of analysis recommended in this manual lead to draft-storage relations having stated probabilities of failure.

Methods Available

When the demands for water exceed the naturally occurring streamflow, the water resources planner first considers storage to hold some of the high flow each year for release during a later period of low flow. This is seasonal or within-year storage. As the demand for water increases and there is not enough high flow every year to raise the low flow to the desired level, extra water must be stored during wetter years for release during dry years. The storage required for this purpose is here termed "over-year" or "carryover" storage.

For many years storage requirements were obtained by analyses of curves of cumulated discharge plotted against time. The storage thus obtained includes both the seasonal and carryover storage that would have been required during the period of record. More recently the analysis of long synthetic sequences of streamflow likewise does not distinguish between seasonal and carryover storage. Nevertheless there are practical advantages to considering seasonal and carryover storage requirements separately.

Mass curve for period of record

Storage analyses have traditionally been based on the mass curve of streamflow. Details are given in most texts on water supply. The mass curve can be obtained by cumulating daily, weekly, or monthly volumes in cfs-days (cubic feet per second-days) or other units. Monthly values are adequate for most water-supply storage analyses, and use of monthly values greatly reduces the work of computation and plotting over that required if daily values are used.

Figure 1 shows a short portion of a mass curve based on monthly values. Any desired constant draft rate can be represented by a straight line of appropriate slope. The maximum draft rate used in the analysis should be somewhat less than the mean flow for the period of record. Mass-curve analysis is usually confined to the most critical period in the record, but it need not be so restricted.

Figure 1 indicates that the maximum storage required for this specific period and for a draft rate of 200 cfs is 960 cfs-months. This result is based on the assumptions (1) that the reservoir was full at the beginning of the period, and (2) that as long as there is water in the reservoir the demand will be met in full. Obviously, the reliability of the results depends on the representativeness of the period of record. The maximum storage required is sometimes assigned a recurrence interval equal to the period of record used in the analysis but this method of estimating frequency is weak.

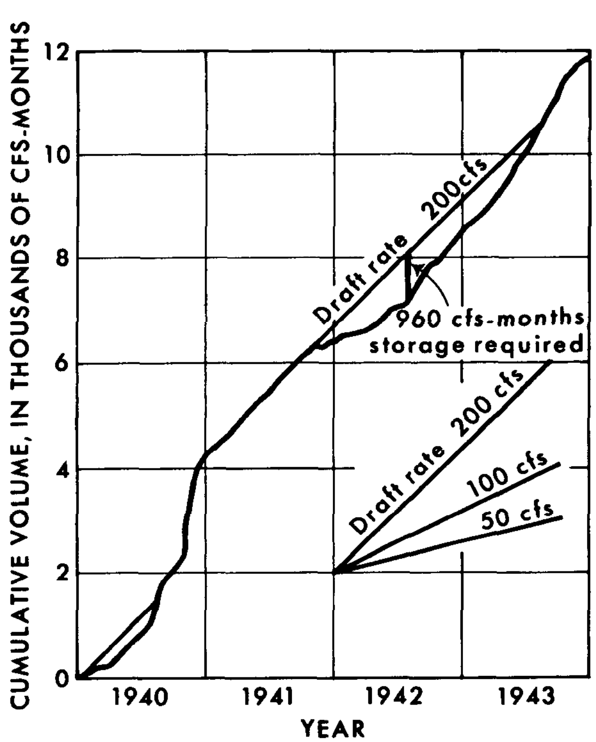


Figure 1.—Mass curve of monthly values, Blackwater River near Union Hall, Va.

The mass curve can also be analyzed for the condition of nonconstant draft rate by preparing the appropriate use line.

Mass-curve analysis is commonly a graphical process but the same results can be obtained arithmetically. Table 1 shows the computations using data on which the graphical solution of figure 1 is based. The addition of a suitable constant (2,000 cfs in table 1) to the cumulated surplus makes all values in the column positive and thus easier to compute.

A related method is described in the "Hydrology Handbook" of the American Society of Civil Engineers (1949, p. 81–83). This method uses the minimum runoffs during the

Table 1.—Storage analysis, Blackwater River near Union Hall, Va.

[Draft rate is 200 cfs]

Month	Mean flow in cfs	Surplus in cfs-months	Cumulative surplus plus 2,000 in cfs-months
1940			
Oct	173	−27	1,973
Nov	222	+22	1,995
Dec	247	47	2,042
1941			
Jan	221	21	[1]2,063
Feb	165	−35	2,028
Mar	166	−34	1,994
Apr	262	+62	2,056
May	142	−58	1,998
June	141	−59	1,939
July	252	+52	1,991
Aug	78	−122	1,869
Sept	77	−123	1,746
Oct	56	−144	1,602
Nov	69	−131	1,471
Dec	113	−87	1,384
1942			
Jan	109	−91	1,293
Feb	120	−80	1,213
Mar	180	−20	1,193
Apr	106	−94	[1]1,099
May	359	+159	1,258
June	312	+112	1,370
July	128	−72	1,298
Aug	267	+67	1,365
Sept	225	25	1,390
Oct	198	−2	1,388
Nov	154	−46	1,342
Dec	268	+68	1,410
1943			
Jan	266	66	1,476
Feb	362	162	1,638
Mar	305	105	1,743
Apr	386	186	1,929
May	398	198	2,127

[1]Storage required: 2,063 (high flow) − 1,099 (low flow) = 964 cfs-months.

period of record for intervals of time ranging from 1 day to 84 months. The method will provide the same results as the mass-curve method of figure 1, if the intervals used increase in length by increments not exceeding 1 month during the critical period.

The mass-curve method does not require, or allow, separation of storage into seasonal and carryover parts. Neither does it permit assignment of a reliable probability of failure to the derived storage.

Use of synthetic streamflows

The storage required to produce a given draft rate depends on the sequence of streamflows. A single record of, say, 25 years may define the flow characteristics of the stream reasonably well but it provides only one 25-year sequence from which to compute storage required. Additional monthly sequences may be generated from the flow characteristics; a recent reference to the method is Fiering and Jackson (1971). By dividing a long synthesized record into n-year periods and analyzing each period by the mass-curve method, a large number of storages are obtained for a given draft rate. These storages then provide a basis for assigning probabilities of failure. An early application of the method is given in Maas and others (1962). Many applications have been reported in the literature since 1962. Burges and Linsley (1971) recently evaluated the method.

This method is used in the design of important projects where streamflow records are available. It has the advantages of permitting the use of variable draft rates and of adjustments for reservoir evaporation and leakage. The method is time consuming and expensive.

Frequency-mass-curve method

Draft-storage-frequency curves may be obtained from a low-flow frequency curve series based on minimum average flows for various period lengths. From a series such as shown in figure 2, a curve relating volume to period of minimum discharge may be prepared for each selected recurrence interval (R. I.). This curve can be analyzed for storage required in the same way as a mass curve of daily or monthly discharge. Figure 3 shows a frequency-mass curve and figure 4 shows storage-required frequency curves derived from frequency-mass curves. The method is described by Martin and Hulme (1957) and Stall (1962). It is appropriate at gaging stations having 20 or more years of record but tends to give storage requirements that are about 10 percent too small (Hardison, 1966).

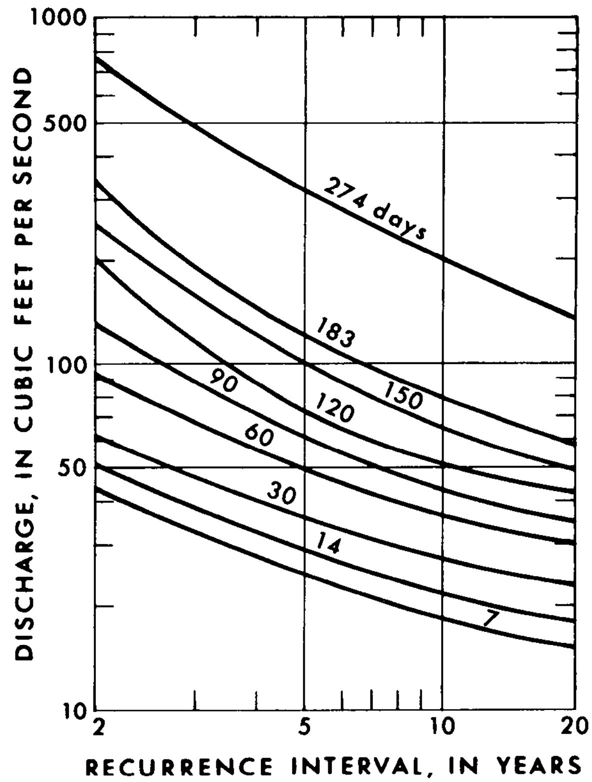


Figure 2.—Low-flow frequency curves.

The low-flow frequency curves of figure 2 may be obtained by computer analysis of daily discharges at the gaging station. The computer program not only selects the minimum flows for periods of 1, 3, 7, 14, 30, 60, 90, 120, 150, and 183 consecutive days for each year of record, but it also makes a frequency plot for each of the periods and fits a log Pearson Type III frequency curve to the points. However, a graphically fitted curve may be preferable (Riggs, 1971). From the resulting family of curves, mass curves of volume versus days for selected recurrence intervals can be prepared. For a 20-year re-

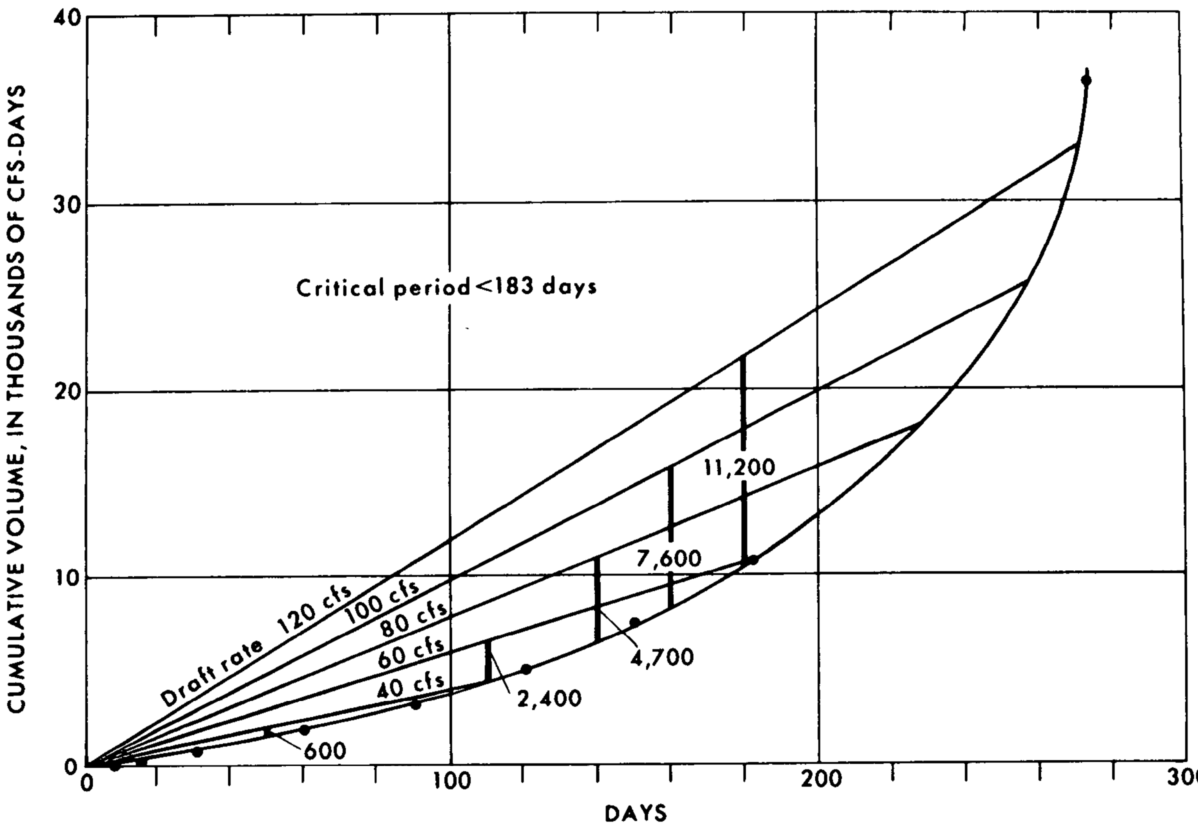


Figure 3.—Frequency-mass curve (20-year recurrence interval).

currence interval, for example, the low flow shown by the 7-day curve (fig. 2) is multiplied by 7 days and plotted against 7 days, the 14-day value is multiplied by 14 and plotted against 14, and so forth to produce the frequency-mass curve of figure 3. Frequency-mass curves usually are prepared for recurrence intervals of 5 and 20 years and for a greater recurrence interval only if justified by the length of record. It is unlikely that a design would be based on a 5-year or smaller recurrence interval but inclusion of such information helps to place the results for higher frequencies (smaller recurrence intervals) in proper perspective.

From the frequency-mass curve of figure 3, storages needed to maintain 4 or 5 selected draft rates can be scaled. If a graphic presentation of results is desired, the storage in cfs-days (or acre-feet) can be plotted against draft rate as shown in figure 4. Curves for other frequencies may also be plotted on the same graph. The result is a storage-draft-frequency relation.

Determination of storages corresponding to selected draft rates may be computed as illustrated in table 2 instead of being obtained graphically as in figure 3. The arithmetic procedure is more accurate at low draft rates but is limited to computation of storages at the points tabulated. If the frequency-mass curve has considerable curvature between the tabulated points, the storage determined arithmetically will be slightly smaller than that obtained from the frequency-mass curve. For most streams the difference will be negligible if the maximum storages required occur at less than 183 days. The cfs-days in italic type in table 2 are the storages required; they correspond to the storages shown in figure 3.

The drafts computed by this method are limited to those which can be provided by a storage volume which will be replaced each

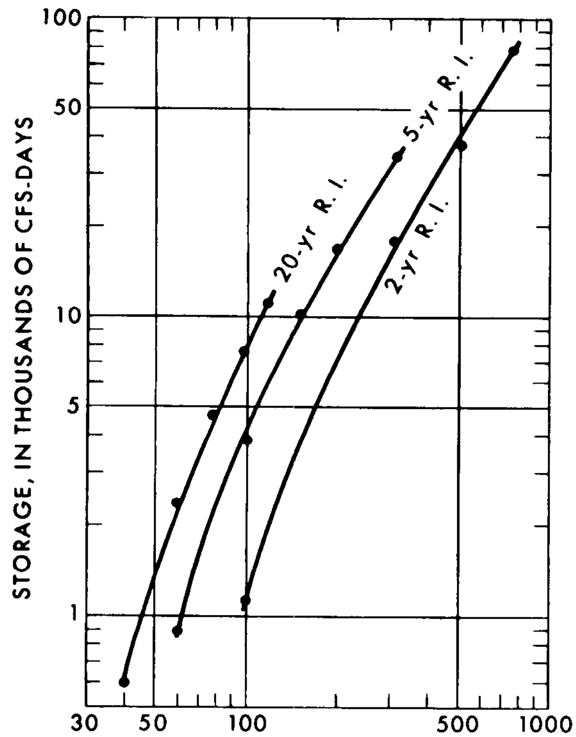


Figure 4.—Storage-draft-frequency relations (20-year points from fig. 3).

year. The method can be extended to higher draft rates by preparing frequency curves for independent low-flow periods greater than 1 year. The interpretation of such curves is described by Stall and Neill (1961) and is discussed by Riggs (1963) and Hardison and Furness (1963). Apparently, the frequency curves for low-flow periods greater than 1 year cannot be interpreted in the same way as those for periods of less than a year. However, the results obtained by use of these curves are in general agreement with those obtained by other methods for the higher recurrence intervals.

Mass curve analysis of flows for each year

The mass-curve method, either graphical or analytical, can be used to define the storage required for a given draft rate for each year of record. From these storages a set of draft-storage-frequency curves can be prepared. Results are limited to draft rates that depend only on the streamflow available in 1 year; that is, on within-year storage. The usefulness of this analysis depends on the within-year variability of streamflow. In some regions, the maximum draft that can be provided by within-year storage is less than a tenth of the mean flow. In others, notably the Southeastern United States, drafts of half or more of the mean flow can be provided by within-year storage.

Daily, rather than monthly, discharges should be cumulated. In many parts of the United States the year beginning April 1 is appropriate because a reservoir would most likely be full on that date.

The computation and plotting of a mass curve on a daily basis is time consuming. The process of cumulation can be simplified by an arithmetic analysis using monthly values except during the critical dates of high and low storage. Table 3 is an example of such an analysis. Note that it is necessary to check whether the reservoir would refill by March 31. In the example (see footnote 2) it did not. Thus the draft rate of 100 cfs would require over-year storage and the analysis of within-year storage should be limited to a smaller draft rate.

Even analyses such as those shown in table

Table 2.—Arithmetic computation of storage from frequency-mass data

Annual minimum flow (20-yr R. I.)			Cfs-days at draft rates indicated and difference (Diff.) from cfs-days in column 3									
Consecutive days	Cfs	Cfs-days	40	Diff.	60	Diff.	80	Diff.	100	Diff.	120	Diff.
7-day	15	105	280									
14	18	252	600									
30	23	690	1,200	510								
60	30	1,800	2,400	*600*	3,600	1,800						
90	35	3,150	3,600	450	5,400	*2,250*	7,200	4,050				
120	42	5,040	—	—	7,200	2,160	9,600	4,560				
150	49	7,350	—	—	9,000	1,650	12,000	*4,650*	15,000	*7,650*	18,000	10,650
183	59	10,800	—	—	—	—	14,640	3,840	18,300	7,500	21,960	*11,160*
274	133	36,400	—	—	—	—	—	—	27,400	—	32,880	—

Table 3.—Mass analysis of daily discharges for Moosup River at Moosup, Conn., April 1, 1943, to March 31, 1944

[Draft rate is 100 cfs]

Month	Total flow in cfs-days	Draft in cfs-days	Surplus in cfs-days	Cumulative surplus plus 10,000 in cfs-days
Apr	5,821	3,000	2,821	12,821
May	6,998	3,100	3,898	16,719
June 1–4	577	400	177	[1]16,896
5–30	1,521	2,600	−1,079	15,817
July	1,072	3,100	−2,028	13,789
Aug	772	3,100	−2,328	11,461
Sept	375	3,000	−2,625	8,836
Oct	1,263	3,100	−1,837	6,999
Nov	2,952	3,000	−48	6,951
Dec	1,734	3,100	−1,366	5,585
Jan	1,861	3,100	−1,239	4,346
Feb. 1–14	641	1,400	−759	[1]3,587
15–29	2,407	1,500	+907	4,494
Mar	7,594	3,100	4,494	[2]8,988

[1]Storage required: 16,896 (high flow) − 3,587 (low flow) = 13,309 cfs-days.

[2]Deficiency on March 31: 13,309 (storage required) − [8,988 (Mar. 31) − 3,587 (low flow)] = 7,908 cfs-days.

3 are time consuming if several draft rates are studied. The analyses can be made quickly by computer. Tapes of daily discharges, and the selected draft rates, are the required input. The ANSTOR program of the Geological Survey assumes a full reservoir on April 1 and, for each of several draft rates, computes the annual maximum depletions (which are the storages required). In addition, the program provides the volume, if any, needed to refill the reservoir at the end of each year. Table 4 shows output of this program for the same gaging station record analyzed in table 3. Italic figures indicate that the tabulated storage required was not replenished by the following April 1 and therefore, the corresponding draft cannot be maintained by within-year storage. (The amounts by which the reservoir would lack being full on March 31 of 1943 and 1949 are obtained as part of the output but are not shown in table 4.) The maximum draft rate selected for entry in the program should be somewhat less than the smallest annual mean of record.

Table 4.—Output of computer program for within-year storage, Moosup River at Moosup, Conn.

[Italic figures indicate that the tabulated storage was not replenished by the following April 1]

Year	Storage, in cfs-days, required to maintain the draft rates indicated during year beginning April 1: 20 cfs	40 cfs	60 cfs	100 cfs
1933	36	568	1,928	5,207
1934	82	978	2,385	5,689
1935	170	1,614	3,979	11,409
1936	80	1,333	3,054	9,989
1937	20	315	1,251	5,997
1938	10	41	116	799
1939	25	761	2,195	8,076
1940	19	371	2,156	6,436
1941	361	1,939	5,023	12,813
1942	25	412	1,445	6,000
1943	319	1,912	4,438	*13,308*
1944	301	1,501	2,926	6,511
1945	62	1,557	3,854	9,108
1946	24	282	1,062	5,617
1947	85	926	2,897	8,239
1948	113	1,124	2,708	7,317
1949	139	2,157	5,157	*12,469*
1950	83	1,115	3,697	9,790
1951	34	652	2,660	7,756
1952	44	1,293	3,903	10,677
1953	378	2,153	4,580	11,009
1954	21	274	1,347	4,716
1955	29	370	1,010	2,735
1956	81	1,253	3,772	10,079
1957	1,092	4,127	8,005	16,535
1958	14	54	269	1,625
1959	145	1,143	2,731	6,328

Frequency curves of storage required to maintain draft rates of 20, 40, and 60 cfs, prepared from the computer output of table 4, are shown in figure 5. Only the higher half

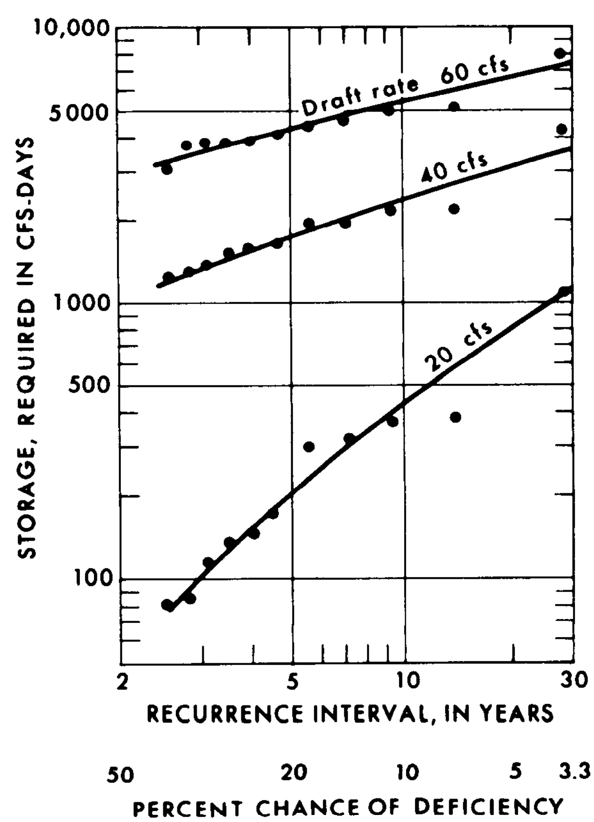


Figure 5.—Draft-storage-frequency curves for Moosup River at Moosup, Conn.

or third of the points computed in table 4 need be used because the definition of the lower part of the curve is not of interest. No curve for a draft of 100 cfs is shown because that draft could not have been provided from within-year storage in 1943 and 1949. A draft rate of 80 cfs should have been included in the computer program.

Probability routing

A principal weakness of the method of analyzing the mass curve for the period of record is the unreliability of the probability that would be assigned to the maximum storage required. This weakness can be overcome by a combination of the probability-routing method and the annual-mass-curve method. Results of the probability-routing method (after adjustment for seasonal variations) define that part of the draft-storage relation which depends on over-year storage. The annual-mass-curve method defines the relation for lower draft rates.

Probability routing is applied to a distribution of annual discharges under the assumptions that the discharge for each year is uniform throughout that year and is equal to the mean for that year and that the annual discharges are not serially related. The procedure was proposed by Langbein (1958) and was described by Hardison and Furness (1963).

Briefly stated, probability routing is based on assuming a distribution for start-of-year reservoir contents and then, for a given draft rate and given frequency distribution of inflow, computing the distribution of year-end reservoir contents to see if it checks the assumed start-of-the-year distribution. (The end-of-year probability distribution of reservoir contents is inherently equal to the start-of-year distribution.) The computations are begun by subdividing the reservoir capacity into about 15 layers and assuming a probability for each layer as well as a probability of spill and a probability of being empty.

The year-end probability for each state is computed by multiplying the assumed probability of each of the possible states by the deficiency probability of the inflow required to produce the selected year-end state and cumulating the products. Agreement could be reached by trial and error solution starting each time with the previously computed year-end distribution, but with an electronic computer a more feasible way is to solve 15 to 20 simultaneous equations to obtain the unique distribution of year-end reservoir contents for the given storage capacity and given draft rate. Each of these equations gives the probability of the water level being in one of 15 to 20 states at the end of the year and the solution is based on the fact that the sum of the probabilities must equal unity. The probability of the reservoir being empty at the end of the year thus obtained is the desired information for the draft rate, reservoir capacity, and inflow distribution used in setting up the equations.

Probability routing can be performed for any distribution of annual inflows, but by characterizing the inflow distributions by a few parameters, the results can be generalized so that it is not necessary to resort to the computer for each problem. Solutions have been obtained for three types of two-parameter distributions and the results have been related to a variability index as summarized in tables 5–7. In table 5, the storage requirements for normal distributions of annual flow are given for probabilities of deficiency in any year of 10, 5, 2, and 1 percent. Similar data for log-normal and Weibull distributions are given in tables 6 and 7 respectively.

Selecting the inflow distribution

The following statistical characteristics of the annual inflows are needed: mean, standard deviation, coefficient of variation, and skew coefficient. These are easily obtained by computer using the Geological Survey flow-variability program. That program (W4422) provides the characteristics based (1) on the untransformed inflows and (2) on the logs of the inflows. Some results are in table 8.

The coefficient of variation for untransformed data, C_v, is the standard deviation divided by the mean; it is an index of variability. The index of variability used for

Table 5.—Carryover storage requirements for normal distributions of annual flows

[Storage requirements are in ratio to mean annual runoff; I_v is standard deviation of the logarithms of annual flows]

I_v	Draft, in percent of mean flow									
	98	95	90	80	70	60	50	40	30	20
				10-percent chance of deficiency						
.08	.65	.40	.21	.05						
.10	.91	.55	.29	.10	0					
.12	1.21	.75	.42	.17	.04					
.14	1.57	1.00	.60	.25	.09	0				
.16	2.00	1.37	.80	.33	.15	.03				
.18	2.47	1.76	1.01	.44	.21	.07				
.20	3.00	2.15	1.23	.56	.28	.11	.01			
.22		2.55	1.48	.69	.36	.16	.04			
.24		2.94	1.76	.84	.45	.21	.07			
.26		3.32	2.10	1.00	.54	.27	.10	.01		
.28		3.71	2.48	1.18	.64	.33	.14	.03		
.30		4.09	2.87	1.37	.74	.40	.18	.06	0	
.40			4.70	2.55	1.47	.85	.45	.24	.10	
.50				4.34	2.59	1.55	.90	.50	.25	
				5-percent chance of deficiency						
.08	1.02	.63	.30	.08						
.10	1.44	.88	.43	.16	.02					
.12	1.96	1.20	.61	.27	.09	0				
.14	2.52	1.59	.83	.40	.18	.05				
.16	3.20	2.10	1.11	.52	.25	.10	0			
.18		2.73	1.45	.67	.33	.15	.03			
.20		3.48	1.85	.83	.42	.21	.07			
.22			2.28	1.02	.53	.28	.11	.01		
.24			2.75	1.22	.65	.35	.15	.04		
.26			3.28	1.45	.77	.42	.19	.07	0	
.28			3.84	1.70	.91	.50	.24	.10	.02	
.30			4.40	1.97	1.06	.60	.30	.13	.04	
.40				3.86	2.11	1.22	.67	.38	.20	.05
.50					3.70	2.20	1.27	.75	.41	.17
				2-percent chance of deficiency						
.08	1.64	.99	.45	.17	.04					
.10	2.30	1.33	.65	.28	.11	0				
.12	3.20	1.73	.90	.40	.20	.05				
.14		2.25	1.19	.54	.29	.11	0			
.16		2.85	1.64	.70	.38	.18	.04			
.18		3.60	2.15	.94	.49	.24	.09			
.20			2.75	1.19	.60	.31	.14	.01		
.22			3.50	1.45	.75	.40	.19	.05		
.24				1.75	.91	.50	.25	.09		
.26				2.08	1.10	.60	.31	.13	.01	
.28				2.42	1.30	.71	.38	.17	.04	
.30				2.80	1.53	.85	.46	.22	.08	0
.40					3.00	1.74	.96	.53	.25	.09
.50						3.10	1.79	1.00	.52	.21
				1-percent chance of deficiency						
.08	2.25	1.13	.58	.18	.06					
.10	3.18	1.68	.81	.30	.13	.01				
.12		2.25	1.18	.47	.23	.07				
.14		3.02	1.59	.67	.34	.14	.02			
.16		3.80	2.15	.90	.46	.22	.07			
.18			2.91	1.17	.60	.30	.12	.03		
.20			3.69	1.47	.74	.38	.18	.06	0	
.22				1.80	.94	.50	.25	.10	.02	
.24				2.18	1.15	.62	.33	.15	.05	
.26				2.60	1.37	.75	.41	.20	.08	0
.28				3.08	1.62	.90	.50	.24	.11	.02
.30				3.60	1.90	1.06	.57	.29	.15	.05
.40					3.67	2.12	1.17	.65	.35	.17
.50						3.75	2.15	1.18	.62	.27

Table 6.—Carryover storage requirements for log-normal distributions of annual flows

[Storage requirements are in ratio to mean annual runoff; C_v is coefficient of variation of annual flows]

C_v	Draft, in percent of mean flow										
	100	98	95	90	80	70	60	50	40	30	20
					10-percent chance of deficiency						
.08	.46	.16	.08	0							
.10	.57	.22	.12	.03							
.12	.68	.30	.17	.06							
.14	.80	.39	.23	.10							
.16	.91	.49	.29	.14	.01						
.18	1.02	.58	.35	.18	.04						
.20	1.14	.68	.42	.23	.07						
.22	1.25	.77	.50	.28	.10						

Table 6.—Carryover storage requirements for log-normal distributions of annual flows—Continued

C_v	Draft, in percent of mean flow										
	100	98	95	90	80	70	60	50	40	30	20
					10-percent chance of deficiency—Continued						
.24	1.36	.87	.58	.33	.13	.01					
.26	1.48	.97	.66	.38	.17	.03					
.28	1.59	1.07	.74	.44	.21	.06					
.30	1.71	1.17	.83	.50	.25	.10	0				
.40	2.28	1.56	1.24	.82	.83	.28	.13	.01			
.50	2.85	2.15	1.65	1.20	.73	.49	.30	.17			
					5-percent chance of deficiency						
.08	1.00	.25	.11	.04							
.10	1.25	.36	.18	.08							
.12	1.50	.50	.26	.12	0						
.14	1.75	.65	.34	.17	.03						
.16	2.01	.81	.43	.23	.06						
.18	2.26	.97	.53	.29	.10						
.20	2.52	1.14	.64	.35	.14	.02					
.22	2.77	1.32	.76	.42	.18	.06					
.24	3.03	1.51	.88	.49	.23	.10	0				
.26	3.28	1.70	1.01	.57	.28	.14	.03				
.28	3.53	1.90	1.14	.65	.34	.18	.06				
.30	3.79	2.10	1.28	.74	.40	.22	.09	0			
.40		3.17	2.02	1.27	.71	.47	.30	.16	.06		
.50		4.30	2.83	1.89	1.07	.75	.53	.37	.24	.13	.03
					2-percent chance of deficiency						
.08		.40	.17	.07							
.10		.60	.25	.13	.01						
.12		.83	.38	.19	.05						
.14		1.08	.51	.26	.10	0					
.16		1.35	.65	.33	.15	.03					
.18		1.64	.80	.42	.20	.07					
.20		1.94	.97	.52	.25	.11	.01				
.22		2.27	1.15	.63	.31	.16	.05				
.24		2.60	1.33	.75	.37	.21	.10	0			
.26		2.95	1.51	.88	.43	.26	.14	.04			
.28		3.30	1.71	1.01	.50	.32	.19	.08			
.30		3.65	1.91	1.15	.57	.38	.23	.12	.02		
.40					1.02	.70	.49	.35	.24	.13	.02
.50					1.60	1.09	.81	.61	.49	.37	.25
					1-percent chance of deficiency						
.08		.48	.21	.10							
.10		.73	.30	.16	.03						
.12		1.02	.43	.24	.08						
.14		1.33	.60	.32	.14	.03					
.16		1.69	.80	.41	.19	.08					
.18		2.09	1.02	.51	.25	.13	.01				
.20		2.52	1.24	.62	.32	.19	.06				
.22		2.97	1.47	.76	.39	.24	.12	.01			
.24		3.45	1.71	.91	.46	.30	.17	.06			
.26			1.96	1.08	.54	.36	.23	.11	0		
.28			2.23	1.26	.62	.42	.28	.16	.05		
.30			2.50	1.45	.71	.48	.33	.21	.10	0	
.40			3.96	2.48	1.28	.87	.64	.48	.36	.25	.11
.50				3.65	2.04	1.32	1.01	.78	.65	.52	.32

Table 7.—Carryover storage requirements for Weibull distributions of annual flow

[Storage requirements are in ratio to mean annual runoff; C_v is coefficient of variation of annual flows]

C_v	Draft, in percent of mean flow										
	100	95	90	80	70	60	50	40	30	20	10
					10-percent chance of deficiency						
.25	1.20	.59	.37	.17	.04						
.30	1.50	.79	.52	.27	.11	0					
.35	1.85	1.00	.68	.38	.18	.05					
.40	2.25	1.23	.85	.48	.25	.11	.02				
.45	2.70	1.48	1.04	.59	.34	.17	.06				
.50	3.15	1.75	1.22	.71	.42	.24	.10	.02			
.55	3.60	2.05	1.44	.84	.51	.31	.14	.05			
.60	4.10	2.36	1.67	.98	.60	.30	.19	.09	0		
.70		3.01	2.13	1.27	.80	.50	.29	.16	.05		
.80		3.67	2.65	1.58	1.01	.65	.40	.24	.10	.01	
.90			3.19	1.93	1.24	.84	.52	.31	.15	.03	
1.0			3.77	2.30	1.48	.98	.64	.40	.20	.05	
1.1				2.70	1.75	1.18	.75	.48	.26	.07	
1.2				3.12	2.02	1.36	.88	.55	.31	.09	
1.3				3.56	2.31	1.55	1.02	.64	.37	.12	
1.4				4.00	2.61	1.74	1.16	.73	.42	.15	
1.5					2.93	1.93	1.30	.82	.48	.19	

Table 7.—Carryover storage requirements for Weibull distributions of annual flow—Continued

Cv	Draft, in percent of mean flow										
	100	95	90	80	70	60	50	40	30	20	10
					5-percent chance of deficiency						
.25	2.40	.96	.59	.30	.15	.04					
.30	3.05	1.25	.80	.41	.23	.11	.01				
.35		1.60	1.03	.54	.32	.17	.05				
.40		2.00	1.29	.68	.42	.24	.10	.03			
.45		2.45	1.55	.83	.53	.31	.15	.07	0		
.50		2.92	1.83	1.00	.64	.39	.20	.11	.02		
.55		3.47	2.15	1.19	.75	.47	.26	.15	.05		
.60		4.02	2.50	1.40	.87	.55	.32	.19	.08	0	
.70			3.24	1.88	1.15	.73	.44	.27	.14	.02	
.80			4.00	2.47	1.44	.95	.59	.36	.19	.05	
.90				3.18	1.77	1.16	.75	.46	.25	.08	0
1.0					2.13	1.38	.91	.56	.31	.11	.01
1.1					2.52	1.62	1.09	.66	.37	.14	.02
1.2					2.95	1.87	1.27	.77	.43	.17	.03
1.3					3.39	2.13	1.45	.88	.50	.21	.04
1.4					3.84	2.40	1.64	.99	.57	.25	.05
1.5						2.66	1.84	1.10	.65	.29	.06
					2-percent chance of deficiency						
.25		1.42	.82	.43	.26	.13	.04				
.30		1.92	1.13	.60	.37	.21	.10	.02			
.35		2.55	1.50	.80	.49	.29	.15	.06			
.40		3.25	1.90	1.00	.62	.38	.21	.10	.02		
.45		3.95	2.32	1.22	.76	.48	.27	.15	.05		
.50			2.80	1.45	.91	.59	.35	.20	.08	.01	
.55			3.30	1.70	1.07	.69	.42	.25	.11	.02	
.60			3.80	1.98	1.25	.80	.50	.29	.14	.04	
.70				2.60	1.63	1.08	.65	.41	.21	.07	
.80				3.28	2.05	1.34	.83	.53	.28	.10	.01
.90					2.50	1.65	1.03	.66	.35	.14	.02
1.0					3.00	2.05	1.25	.79	.42	.17	.03
1.1					3.52	2.30	1.50	.93	.50	.31	.04
1.2					4.05	2.65	1.75	1.08	.58	.25	.05
1.3						3.00	2.01	1.23	.66	.30	.07
1.4						3.40	2.29	1.39	.75	.35	.09
1.5							2.58	1.56	.85	.40	.11
					1-percent chance of deficiency						
.25		1.70	.98	.50	.33	.20	.08	.01			
.30		2.50	1.45	.73	.47	.30	.15	.05			
.35		3.35	2.00	.97	.60	.38	.21	.10	.02		
.40			2.50	1.23	.75	.49	.28	.15	.05		
.45			3.00	1.50	.92	.59	.35	.20	.08	.02	
.50			3.55	1.83	1.10	.72	.43	.25	.11	.04	
.55				2.18	1.30	.85	.52	.30	.15	.06	
.60				2.55	1.50	.99	.61	.35	.19	.08	
.70				3.30	1.98	1.31	.81	.50	.26	.12	.01
.80					2.50	1.65	1.06	.63	.35	.16	.02
.90					3.13	2.02	1.31	.78	.44	.20	.03
1.0					3.80	2.42	1.57	.94	.54	.24	.05
1.1						2.83	1.84	1.10	.64	.29	.06
1.2						3.26	2.15	1.27	.74	.33	.08
1.3						3.70	2.46	1.46	.84	.38	.10
1.4							2.80	1.65	.95	.44	.12
1.5							3.15	1.85	1.07	.48	.14

logarithms of inflow is the standard deviation of the logarithms, I_v.

The coefficient of skew is

$$C_s = \frac{N(\Sigma d^3)}{(N-1)(N-2)(SD)^3}$$

in which d is deviation from the mean, SD is standard deviation, and N is the number of items in the sample. If the logarithms of the inflows are entered in the above equation the coefficient of skew is called g rather than C_s.

Referring again to table 8 for Sangamon River at Monticello, the characteristics of the untransformed inflows should be obvious; using logarithms of inflows, I_v=.266, and g=−.919.

The appropriate distribution is selected on basis of the criteria given in table 9.

The criteria were developed by comparing how well the distribution curves for each of the three types of distributions agreed with the shapes of graphical curves based on distributions of observed annual discharge at many long-term stream-gaging stations. The annual discharges and the distribution curves were plotted on log probability paper to appraise the fit visually.

If there is any question about use of the criteria of table 9 for a particular site the annual inflows may be plotted on probability paper along with the theoretical curve indi-

Table 8.—Statistics of annual discharge computed by digital computer

[Standard deviation of the logarithms is the index of variability. Letters in parentheses preceding skew coefficient indicate type of distribution selected in accordance with criteria given in table 9: W, Weibull; N, normal; LN, log normal]

Unit of annual discharge	Mean	Standard deviation	Coefficient of variation	Skew coefficient	First order serial correlation coefficient
Sangamon River at Monticello, Ill., station 05-5720 for water years 1915–62					
Cfs	396.40	206.97	0.522	(W) 0.915	0.249
Logs of cfs	2.53043	.266	----	−.919	.266
River Rouge at Detroit, Mich., Station 04-1665 for water years 1931–63					
Cfs	108.57	47.03	0.433	(W) 0.556	0.196
Logs of cfs	1.99314	.203	----	−.572	.246
Miami River at Taylorsville, Ohio, station 03-2630 for water years 1922–62					
Cfs	977.51	390.14	0.399	(N) −0.201	0.245
Logs of cfs	2.94648	.212	----	−.914	.192
Raccoon Creek at Adamsville, Ohio, station 03-2020 for water years 1939–62					
Cfs	623.12	193.92	0.311	(N) −0.383	0.021
Logs of cfs	2.76914	.163	----	−1.340	.084
Red River near Adams, Tenn., station 03-4355 for water years 1921–62					
Cfs	970.61	402.07	0.414	(W) 0.649	0.197
Logs of cfs	2.94786	.194	----	−.598	.176
Cacapon River near Great Cacapon, W. Va., station 01-6115 for water years 1924–61					
Cfs	585.44	207.84	0.367	(W) 0.322	−0.172
Logs of cfs	2.72185	.169	----	−.330	−.177
Mattawamkeg River at Mattawamkeg, Maine, station 01-0310 for water years 1903–34					
Cfs	2657.12	636.08	0.239	−0.108	0.104
Logs of cfs	3.41121	.111	----	(N) − .679	.082
Mattawamkeg River near Mattawamkeg, Maine, station 01-0305 for water years 1935–62					
Cfs	2420.25	593.95	0.245	0.211	0.038
Logs of cfs	3.37084	.109	----	(N) −.241	.051
Tombigbee River at Columbus, Miss., station 02-4415 for water years 1929–62					
Cfs	6314.71	2443.33	0.386	0.556	0.251
Logs of cfs	3.76810	.172	----	(LN) −.179	.234

cated by table 9 for a visual check. Normal and log-normal curves can be plotted using a table of normal deviates, but the computation of the Weibull curve is more complicated; use of the diagram of figure 6 for the Weibull curve will simplify the procedure.

Defining the draft-storage-probability relation

Having selected the appropriate inflow distribution, the draft-storage relations for selected chances of deficiency may be plotted from the data given in tables 5–7. Note that these relations are based on the assumption

Table 9.—Criteria for selecting type of distribution

[C_v, coefficient of variation; C_s, skew coefficient of cfs; g, skew coefficient of logs]

C_v	g: +0.5 to −0.2	g: −0.2 to −1.5
0 to 0.25	Log normal	Normal.
0.25 to 2.0	Log normal	Normal if C_s is < 0.2. Weibull if C_s is > 0.2.

that the discharge throughout each year is uniform and equal to the mean for that year. Thus, the storage shown needs to be increased to account for the within-year variability of flow. The seasonal storage to be added increases linearly from the computed maximum within-year storage of 0.4 mean annual volume at a draft rate of the mean flow. The upper limit of 0.4 was obtained by a method proposed by Beard (1964); it is the average of computed values for several stations scattered throughout the United States.

The Recommended Method at Gaging Stations

The mission of the Geological Survey is to appraise available resources. The method of defining draft-storage-frequency relations recommended here is intended to produce results which will be used as a guide in planning and in preliminary design. The actual design of a storage reservoir must take into account the reservoir site, evaporation, possible leakage, and other factors. For important projects a more sophisticated hydrologic analysis would be made.

For defining the draft available from within-year storage (that which will be replenished each year) use the method described under "Mass Curve Analysis of Flows for Each Year." For carryover storage use the probability-routing method in combination with the mass curve analysis of flows for each year. The following example provides details.

Application to Red River near Adams, Tennessee

Use ANSTOR computer program to get storages for each year for selected draft rates. The maximum draft rate selected was 250 cfs, slightly less than the smallest annual mean. Table 10 lists pertinent output from

Table 10.—Output of computer program for within-year storage, Red River near Adams, Tenn.

[Italic figures indicate that the tabulated storage was not replenished by the following April 1]

Year	Storage, in cfs-days, required to maintain the draft rate indicated during year beginning April 1: 50 cfs	100 cfs	150 cfs	200 cfs	250 cfs
1921		256	980	2,373	6,241
1922	12	1,030	5,197	10,398	16,148
1923		18	645	2,367	4,611
1924	10	1,153	3,001	6,231	9,759
1925	82	1,293	5,362	9,968	14,778
1926		197	1,342	2,730	4,778
1927		186	1,844	3,782	6,149
1928			195	1,666	3,697
1929		561	1,983	4,896	8,493
1930	123	5,859	16,682	28,003	*39,689*
1931	6	1,264	4,796	9,179	17,213
1932		57	904	2,233	5,332
1933		133	1,249	6,511	13,019
1934		38	425	1,063	3,575
1935		81	2,294	6,755	12,351
1936	12	1,004	3,558	6,887	13,841
1937		467	2,258	4,911	11,729
1938		12	761	2,809	6,812
1939	13	4,312	12,284	21,116	30,188
1940	34	2,638	7,082	14,430	*23,450*
1941	16	2,223	6,355	10,881	18,239
1942		124	2,335	5,526	8,795
1943	11	832	6,057	13,626	21,855
1944		292	2,056	4,877	8,291
1945		968	5,045	10,546	16,956
1946	63	2,253	9,971	19,248	28,742
1947	14	1,984	6,208	12,796	21,215
1948	333	3,472	7,537	12,376	19,043
1949			528	2,422	7,098
1950					109
1951		119	1,227	2,765	6,279
1952	8	3,311	10,569	19,863	30,858
1953	420	6,539	15,022	23,698	33,016
1954		1,471	4,628	10,713	18,546
1955		1,299	8,861	17,016	26,711
1956	127	4,039	9,413	16,499	27,363
1957		547	2,689	7,386	13,493
1958		286	4,636	10,347	17,329
1959		293	1,891	5,562	13,427
1960		1,275	5,488	11,540	18,265
1961		829	3,803	8,376	13,337
1962		268	1,723	4,741	15,273

the ANSTOR porgram for Red River near Adams, Tenn., for the period 1921–62. (The italic figures indicate that the tabulated storage was not replenished by the following April 1.) Frequency curves of storages for the tabulated draft rates are shown in figure 7; these were prepared graphically from the data of table 10.

As the first step in computing carryover-storage requirements, the statistics of annual

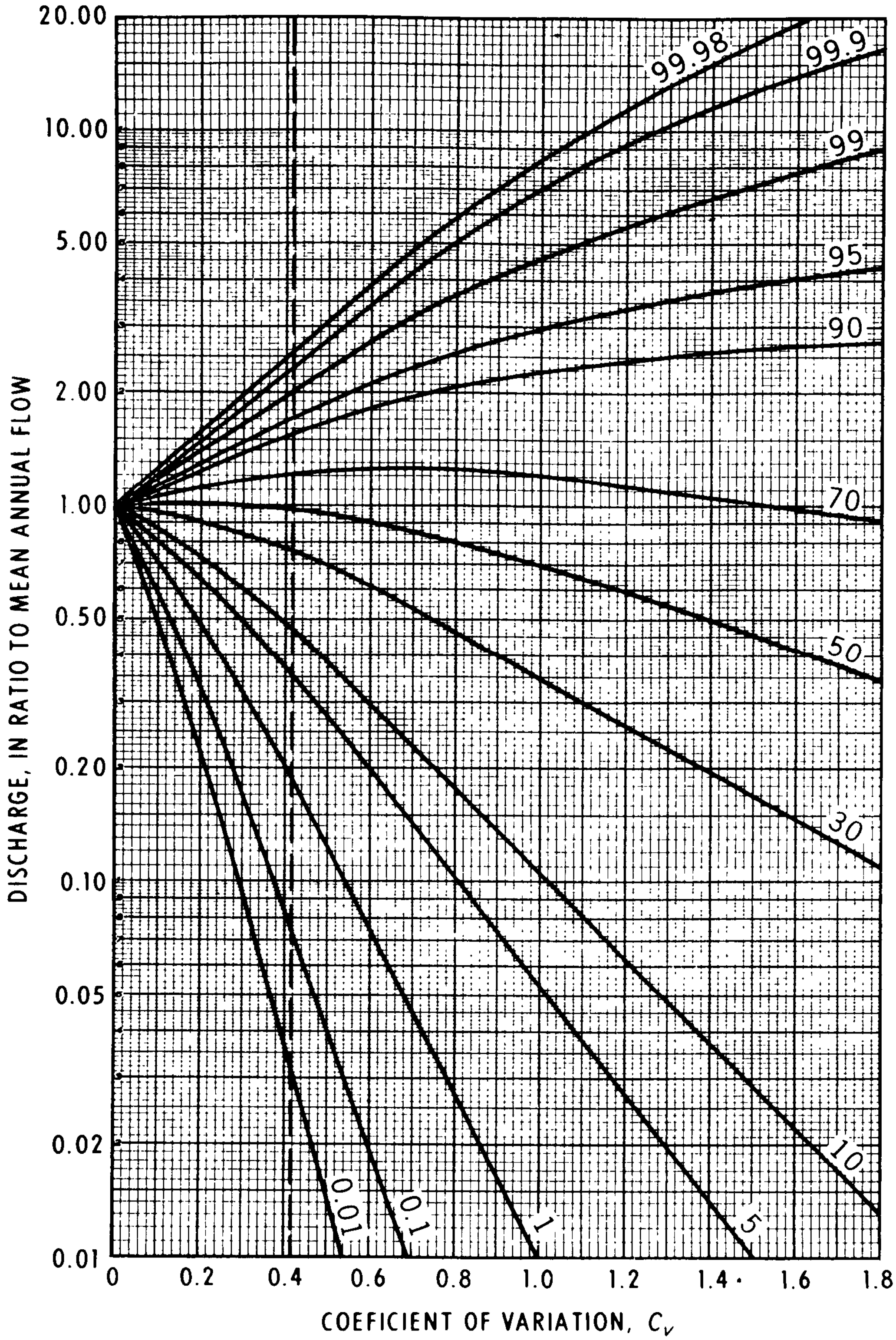
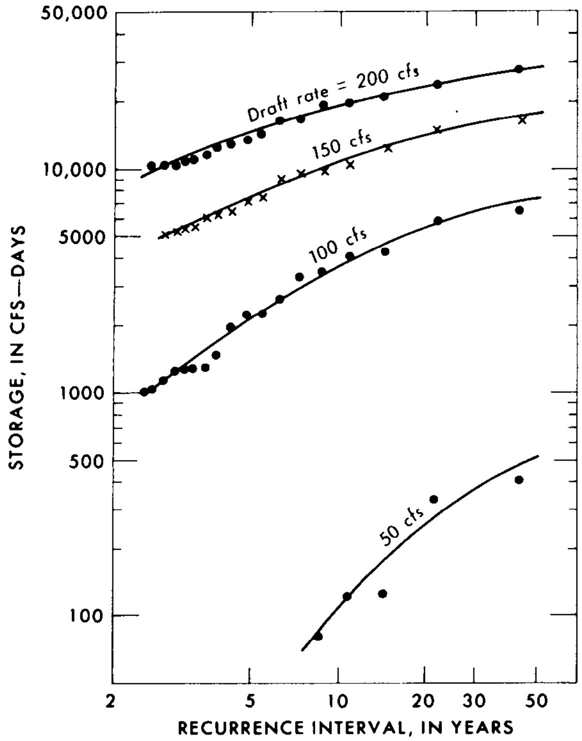


Figure 6.—Construction diagram for plotting Weibull distribution.



discharge for Red River near Adams, Tenn., given in table 8 are used to select the type of distribution by use of the criteria given in table 9. The fact that the skew coefficient of the logarithms (−0.598) is algebraically less than −0.2 precludes the use of a log-normal distribution, and the facts that the coefficient of variation (0.414) is greater than 0.25 and the skew coefficient of the discharge (0.649) is algebraically greater than 0.2 precludes the use of a normal distribution. Thus table 9 indicates that a Weibull distribution should be used and that the computed coefficient of variation (0.414) should be used as the variability index. Figure 8 verifies that the Weibull distribution fits the sample data better than the other two distributions. (This test is not part of the recommended procedure; it is included only to show that the criteria of table 9 led to the correct selection.)

Figure 7.—Draft-storage-frequency curves for Red River near Adams, Tenn.

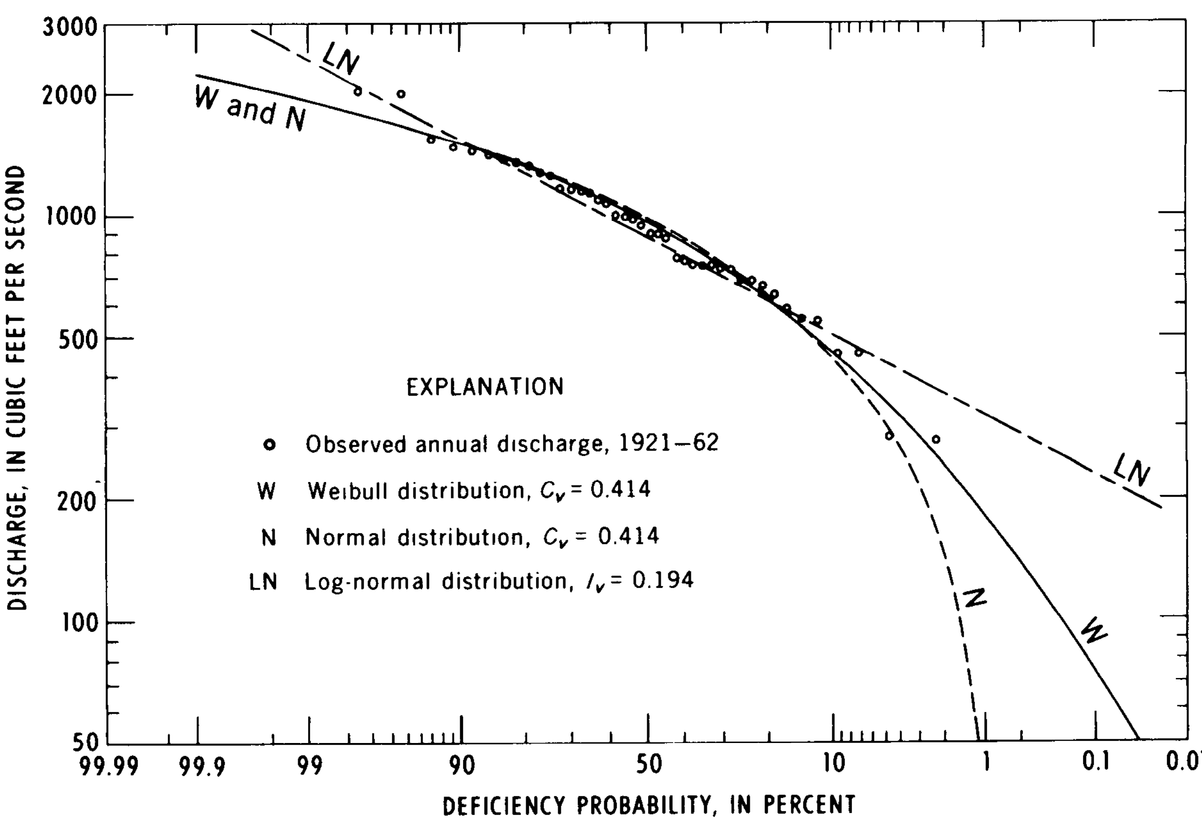


Figure 8.—Probability distribution of annual discharges for Red River near Adams, Tenn., showing the fits of three types of distribution curves.

Having selected the type of distribution, the carryover storage requirements can be selected from table 7. Those for 2-percent chance of deficiency are listed in columns 2 and 3 of table 11. Results for the three other chances of deficiency can be obtained similarly but this example is limited to the 2-percent chance.

Within-year drafts and the corresponding storages are taken from the frequency curves of figure 7 and are listed in columns 1 and 4 of table 11. Then the drafts in percent of mean and the storages in ratio to mean annual runoff (MAR) are computed and entered in columns 2 and 5 respectively. These within-year storage ratios are also listed in the last column.

Adjustments to carryover storage are required to compensate for the assumption in probability routing that the annual mean does not vary throughout the year. These adjustments can be made as follows:

1. Plot the within-year draft-storage relation as shown in figure 9 and draw a straight line from its upper end to the point having coordinates of 100 percent draft and 0.4 storage capacity.
2. From this line read the storages corresponding to the drafts listed in column 2 of table 11, and enter in column 6.
3. Add the seasonal adjustment and carryover storages and enter in last column.

The final draft storage curve is defined by the plot of column 2 against column 7 of table 11, as shown in figure 9.

To complete the analysis of storage requirements for Red River, the steps for the 2-percent chance of deficiency should be repeated for the 1, 5, and 10-percent chances so that a diagram such as that shown in figure 10 can be prepared to demonstrate that an increase in the allowable draft is made possible by accepting a chance of more frequent deficiency as well as by providing a larger reservoir. Whether the cost of the more frequent deficiency is greater than the cost of the additional reservoir capacity depends largely on economic factors. Modification of those draft-storage curves to account for the effects of evaporation, serial correlation, and other factors are discussed in the final section of this report.

Defining Draft-Storage Relations at Ungaged Sites

Definition of draft-storage-frequency relations at sites having no streamflow records is often required. This may be done in two ways: (1) by estimating the statistics of monthly flows from generalized relations with basin characteristics, and synthesizing a long flow record (Benson and Matalas, 1967), and (2) by generalizing the draft-

Table 11.—Computation of draft-storage relation for Red River near Adams, Tenn. (2-percent chance of deficiency)

[Mean flow=971 cfs; mean annual runoff (MAR)=354,000 cfs-days]

Draft		Storage				
			Seasonal			
Cfs (1)	Percent of mean (2)	Carryover, in ratio to MAR (3)	Cfs-days (4)	Ratio to MAR (5)	Seasonal adjustment ratio to MAR (6)	Total ratio to MAR (7)
922	95	3.45	----	----	.38	3.83
874	90	2.02	----	----	.36	2.38
777	80	1.06	----	----	.33	1.39
680	70	.66	----	----	.29	.95
583	60	.41	----	----	.25	.66
486	50	.23	----	----	.21	.44
388	40	.11	----	----	.18	.29
291	30	.03	----	----	.14	.17
200	20.6	----	28,000	.079	----	.079
150	15.5	----	18,000	.051	----	.051
100	10.3	----	7,500	.021	----	.021
50	5.2	----	500	.001	----	.001

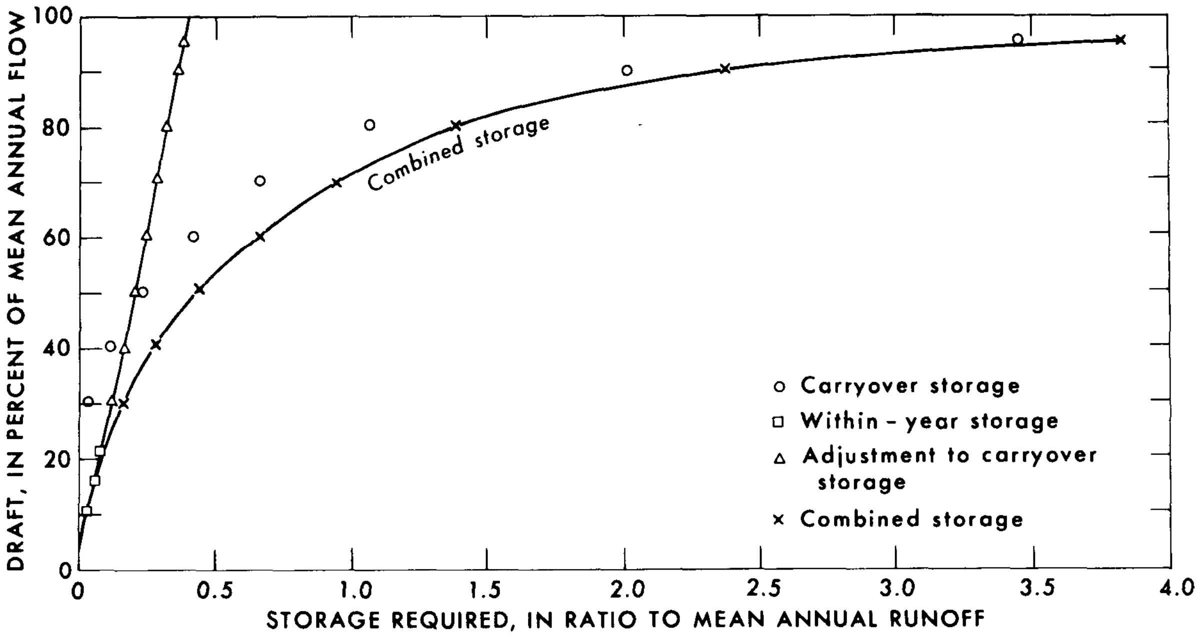


Figure 9.—Combination of within-year and carryover storage requirements for a 2-percent chance of deficiency, Red River near Adams, Tenn.

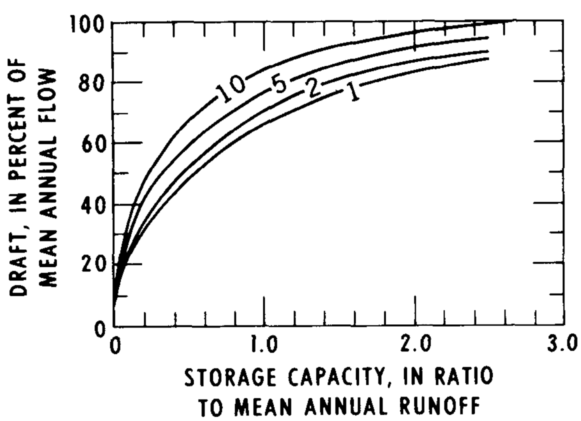


Figure 10.—Storage-draft-frequency relations, Red River near Adams, Tenn.

storage-frequency relations directly. The first method is not appropriate for a general report on draft-storage characteristics in a region because application to a specific site requires a great deal of work by the user. Therefore, the second method is recommended and described here.

Transferring a draft-storage relation is accomplished by use of a regional relation in conjunction with some streamflow information collected or estimated at the site. Two criteria must be met: (1) draft-storage relations defined by gaging-station records for various recurrence intervals must be closely related to flow characteristics; (2) sufficient information must be available at the site of application to provide good estimates of the flow characteristics needed in the regional relation. Drainage area is used in some regional relations. Mean flow and median annual minimum 7-day flow also are commonly used; these can be estimated as described by Riggs (1965).

Regional draft-storage relations are usually developed graphically because some of the models are difficult to express mathematically. The choice of variables will depend on flow characteristics in the region and on what information is available. However, the draft and the storage should be in units commonly used or readily computed. For example, draft should be in cfs, cfs per square mile, or in ratio to the mean flow; storage should be in acre-feet, millions of gallons, or in terms of unit area or mean annual runoff.

Various relations (from Riggs, 1966) are shown in figures 11 to 13. Figure 11, for Tar River basin, North Carolina, uses drainage

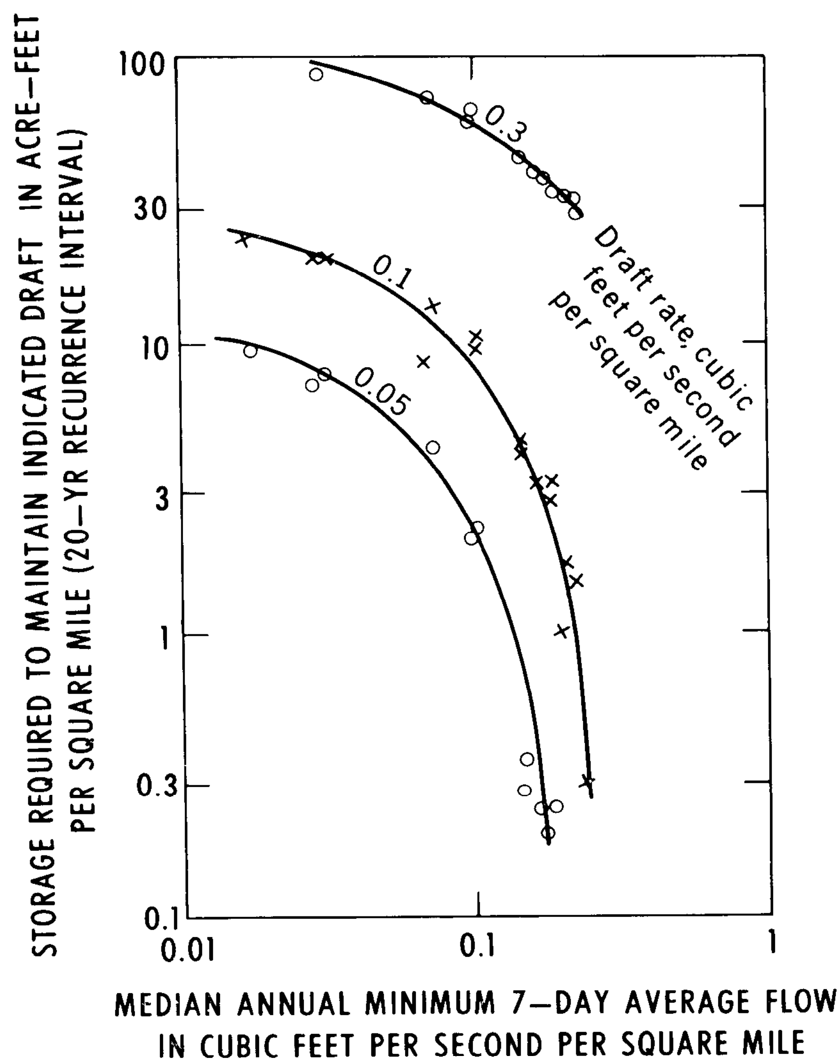


Figure 11.—Regional storage-draft relations for Tar River basin, North Carolina.

area and a low-flow characteristic. Figure 12, for some Illinois streams, uses mean flow and a low-flow characteristic. The relation for Kansas River basin, figure 13, uses mean flow and a streamflow-variability index; the low-flow characteristic is zero for many of these streams.

Figure 14 is taken from a recent report by Skelton (1971). In an earlier report Patterson (1967) related draft rate in ratio to mean flow to (1) a low-flow characteristic and (2) storage in ratio to mean annual flow volume.

Regional draft-storage relations should not be extrapolated beyond the data in either direction.

Modifications to Draft-Storage Relations

Evaporation losses

Although a draft-storage relation derived by the method recommended in this report continues to show an increase in allowable draft even at the extreme upper end, this does not mean that the usable outflow from the reservoir would continue to increase. As the allowable draft is increased, the evaporation loss from the increased amount of required storage may more than offset the increase in draft. The amount of this loss de-

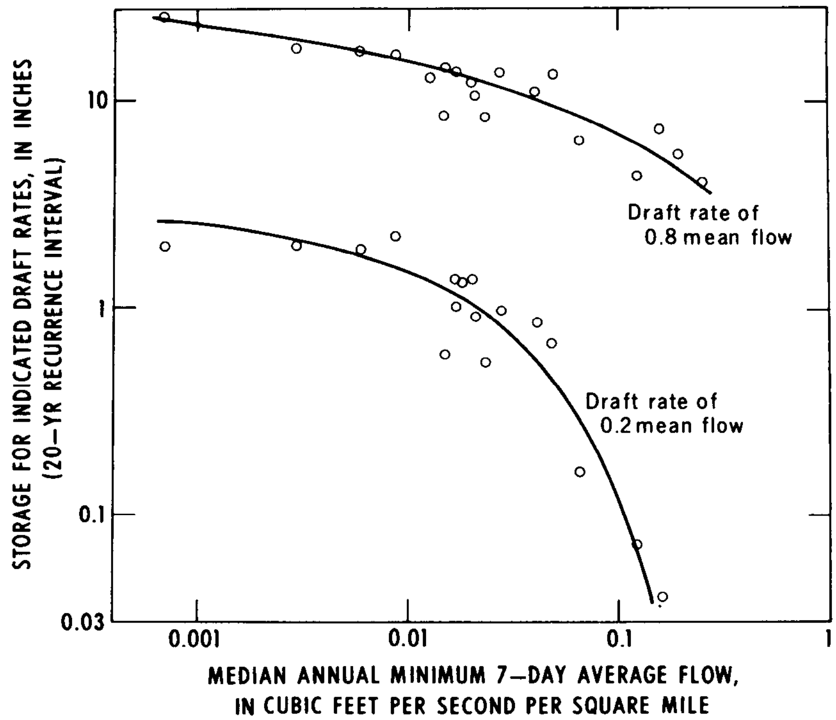


Figure 12.—Regional storage-draft relations based on data for some Illinois streams.

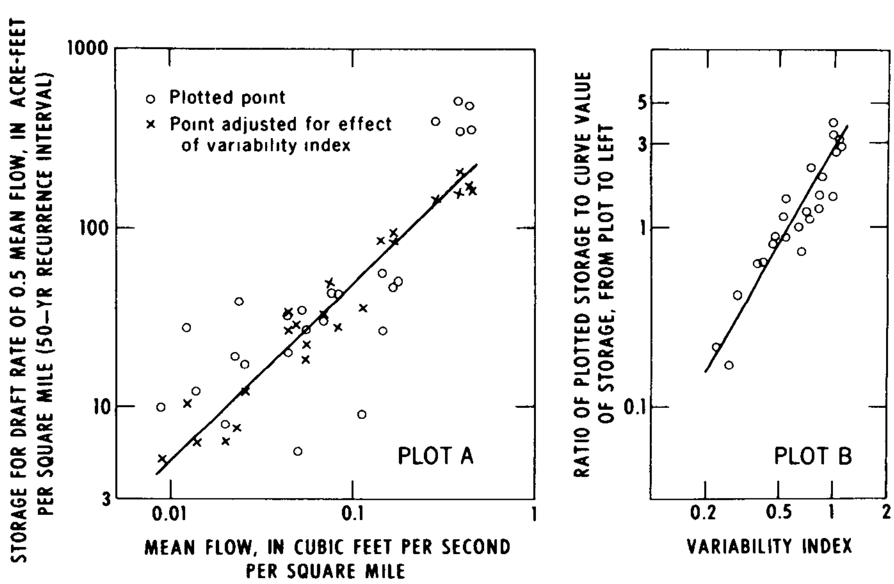


Figure 13.—Storage related to mean flow and variability index in Kansas River basin.

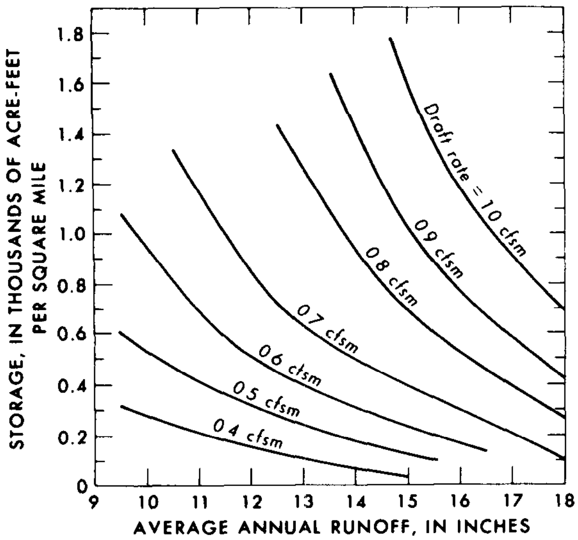


Figure 14.—Draft-storage curves for a region in Missouri, 2-percent chance of deficiency (from Skelton, 1971).

pends on the surface area of the reservoirs, on the amount by which evaporation from a reservoir exceeds the natural water loss from the land and vegetation that previously occupied the reservoir area, and on the time between reservoir refillings. If, for example, the annual net evaporation loss for reservoir sites upstream from Red River near Adams, Tenn., averages 3 percent of the storage capacity as used by Lof and Hardison (1966, p. 348) for the Cumberland region, the 1.5-percent increase in draft shown in figure 9 between storage capacities of 3.0 and 3.5 would be entirely offset by increased evaporation loss. Therefore, the fact that evaporation losses have been considered to be part of the draft rate should be clearly stated in any presentation of results.

Stall (1964, p. 39) illustrates the computation of net evaporation loss for a specific reservoir. In his example the reduction in draft rate due to evaporation is substantial.

Effect of serial correlation

When the annual discharges (inflows) are related to each other so that a year of low flow is more likely to follow a year of low flow than a year of high flow, more storage will be required to maintain the same draft rate than if the flows were independent as assumed in the probability routing analyses on which tables 5-7 are based. The first-order serial correlation coefficient can be used to estimate the effect of serial correlation on draft rate for a given storage according to a method developed by Hardison (1966). His analyses indicate that for a storage-drawdown period of 2 years and a first-order serial correlation coefficient of 0.2, the draft for a given storage should be reduced by about 5 percent of the mean annual flow.

Although the computed serial correlation coefficient for Red River near Adams, Tenn., shown in the last column of table 8 is nearly 0.2, additional study would be required before this could be accepted as the true serial correlation coefficient of a longer period of years at this station. (Although the observed serial correlation is not statistically significant at the 5-percent level, the fact that the average serial correlation of annual discharges of 180 streams well distributed throughout the United States is 0.17 indicates that serial correlation may exist even where not significantly different from zero in a specific sample.) It is recommended that the possibility of serial correlation be discussed in any report on storage requirements at high draft rates but that adjustments for this effect be left to the discretion of the user.

Other factors

The method recommended in this manual does not permit evaluation of the storage required to provide nonuniform draft rates. Nor is this considered necessary for a study in which neither the reservoir site nor the specific demands are known. Use of a nonuniform draft rate tends to increase the storage required where the season of greatest demand is out of phase with the season of greatest streamflow.

In some regions, the amount of storage indicated by the relations cannot be furnished because of unsuitable topography. Cross (1963, p. 7) used an upper limit of

100 million gallons per square mile in Ohio. Dawes and Terstriep (1966) considered runoff, the physical characteristics necessary to impound water, and relative freedom from manmade or natural obstructions in their inventory of potential surface water reservoirs in south-central Illinois.

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