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14. ABSTRACT

The effects of some basic assumptions of simplified methods of reservoir yield forecasting are demonstrated so that techniques may be chose to produce the desired results with the best expenditure of time, funds, and manpower. The techniques for evaluating long-term reservoir yield may be divided into two general categories: (1) non-sequential methods which generally consider only the quantity of water available; and, (2) sequential methods which consider both the quantity of water available and its time distribution. The three factors about which assumptions are frequently made in the simplified techniques are evaporation, seasonal variation in demand, and drought duration. Storage requirements to meet a given yield may be under-estimated by more then forty percent if evaporation and seasonal variation are ignored when they are actually significant. None of the simplified techniques are capable of accounting for all of the factors which affect the yield in a complex multiple-purpose project. The capability now exists to perform these sequential routings by electronic computer, even in the initial planning phases of a study. Furthermore, these routings may be used with generated streamflow data.

15. SUBJECT TERMS
reservoir yield, streamflow forecasting, routing, computer programs, optimization, estimating reservoir operation, water supply, safe yield, probability, statistical methods

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TECHNIQUES FOR EVALUATING LONG-TERM RESERVOIR YIELDS (1)

by AUGUSTINE J. FREDRICH (2)

INTRODUCTION

The ever-increasing demand for water from reservoirs for municipal and industrial requirements, for water quality control and for agricultural uses has caused increased emphasis upon the development of maximum feasible yield at each new reservoir site. Furthermore, because human nature and economic necessity have caused utilization of water in this country to consistently press upon the upper bounds of the available supply, the dependability of existing and future water supplies becomes an increasingly important factor in reservoir yield studies.

The need for maximum feasible development and the need to determine dependability are two reasons that the techniques used to evaluate water yield should allow consideration of all factors which significantly influence the yield from the project. The purpose of this paper is to compare the results of reservoir storage-yield analyses under several different assumptions in order to demonstrate the effects of the assumptions on the analyses.

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(1) For presentation at the ASCE National Meeting on Water Resources Engineering in New Orleans, 8 February 1969.

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PURPOSE OF THE STUDY

Previous work by individuals and agencies concerned with planning, design, and operation of reservoirs and reservoir systems indicates that there are numerous instances where so-called "short-cut" methods do not provide reliable estimates of the water yield available from a reservoir. Likewise, advocates of the "short-cut" methods have demonstrated that, under certain conditions, their techniques do provide reliable estimates at a significant saving of both time and money. What has not been shown, however, are the results of some of the assumptions which are implicit in many of the simplified techniques. The subject study has not been conducted for the purpose of degrading the simplified methods but rather to clearly demonstrate the effects of some basic assumptions so that one may more readily identify instances where these assumptions are significant and thus choose techniques which will produce the desired results with the expenditure of minimum time, funds, and manpower.

The techniques for evaluating long-term reservoir yield may be divided into two general categories: (1) non-sequential methods which generally consider only the quantity of water available; and (2) sequential methods which consider both the quantity of water available and its time distribution. Within each of these two categories there are two subdivisions: (1) deterministic methods which produce yield estimates based upon the streamflow as it actually occurred;

and (2) stochastic methods which provide yield estimates based upon the statistical characteristics of the streamflow data. The intent of this study is to compare techniques from each of the two general categories under a representative variety of hydrologic conditions.

The three factors about which assumptions are frequently made in the simplified techniques are evaporation, seasonal variation in demand, and drought duration. Consequently, this study places emphasis upon the relationship among these three factors, various hydrologic conditions, and the techniques used to determine the yield.

BASIC ASSUMPTIONS

Seven streamflow stations in the United States were selected for this study. Each of the seven locations had a relatively long continuous record of streamflow data, and at each of the seven stations the streamflow data used were essentially unregulated. Furthermore, the seven locations were selected so as to be representative of the wide variety of hydrologic conditions which exist in the United States. Table 1 shows some pertinent physical and statistical data for the selected stations. An area-capacity relationship was developed for each site from examination of topographic characteristics of the site and from analysis of area-capacity data for existing reservoirs nearby. Monthly net evaporation rates were then computed from long-term evaporation and precipitation data at climatological stations near to the streamflow stations. These data were used in the sequential routing studies to simulate evaporation losses reasonably characteristic of each particular region.

A single seasonally varying demand schedule was adopted for use in all aspects of the study relating to the effect of seasonal variations in water demands. It was recognized that the seasonal variations in demand would differ from region to region but, since the purpose of the study is the demonstration of the effect rather than the establishment of quantitative values for use in design studies, the adoption of a single schedule which is reasonably characteristic of several water uses throughout the country is consistent with the study objectives. In the adopted schedule the maximum demand occurred in the three summer months and the maximum monthly demand was 1.92 times the average annual demand. The minimum demands occurred in the months of November, December, January, and February and in each of these months the demand was 0.48 times the average annual demand.

Several other factors which may be important in yield analyses but which are obviously beyond the scope of simplified techniques were not considered in the study. Examples of these factors include multiple demands with different priorities, unusual starting or ending conditions, and complex operating rules.

STUDY PROCEDURE

The procedure used for the study was to determine by monthly sequential routing for the selected period of record the yield (with no shortage) corresponding to each of at least fifteen different storages at each site. The storages were selected so as to produce yields ranging from 10 to 90 percent of the average annual flow. Since the determination of yield by sequential routing techniques is not a direct solution, successive approximations - each approximation consisting of a complete monthly sequential routing for the entire period of historical record - were used to determine the yields. A generalized computer program developed in The Hydrologic Engineering Center, "Reservoir Yield" [1], was modified to perform the successive routings necessary to determine the yield from each storage.

Four sets of routings were made for each of the seven sites. Each set was intended to produce the yields which would be obtained from a reservoir at the site under typically assumed conditions. The four conditions are: 1) no evaporation and no seasonal variation in demand - the traditional mass curve analysis; 2) with evaporation, but without seasonal variation in demand; 3) without evaporation, but with seasonal variation in demand; and 4) with both evaporation and seasonal variations in demand. All other variables such as starting conditions, operating rules, and outlet capacities were the same for all four sets of routings.

The first set of routings produced for each of the seven sites, the yields which one might obtain using a simple mass curve analysis for each of the assumed storages. The time of occurrence and the duration of the critical period were tabulated for each of the assumed storages.

The second set of routings provided the yields and critical periods for the same storages used in the first set but with evaporation included in the analysis. Consequently the results of this set of routings, when compared with the results of the first set, would give an indication of the effect of evaporation on the yield and on the duration of the critical period.

The third set of routings produced the same type of data as the two previous sets and, thus, by comparing the results of this set with the first set, one could assess the effect of seasonal variation in demand; and by comparing the results of this set with the second set a comparison of the relative magnitude of these two effects could be obtained.

The final set produced, for purposes of this study, the yields which would actually be obtained if the assumed projects were constructed. When compared with the results of the first set, these results would indicate the consequences of ignoring evaporation and seasonal variation in demand. Furthermore, comparison of these results with the combined results of the second and third sets would indicate whether the effects of evaporation and seasonal variation are independent or whether there is an interrelationship between the two which would accentuate or diminish the combined effects.

OPTIMIZATION ROUTINE

The key to development of analytical techniques for comparison of many sites at many levels of utilization and under several alternative assumptions is a completely computerized optimization routine for use in the storage-yield analysis. In the past, storage-yield studies by computer have been hampered by the necessity for either human intervention in the successive approximation procedure or unwieldly numbers of trials based on a systematic search scheme. Since the subject study required almost 600 separate yield determinations - each based on more than 40 years of hydrologic record for each trial - it was apparent that the work could not be accomplished at a reasonable cost or in a reasonable amount of time unless a very efficient scheme could be developed to utilize the results of the first sequential routing to estimate the yield available from the specified storage.

Since the objective of the studies was to find the yield, with no shortage, from a given storage, it was not possible to use efficient techniques based upon the shortage index [2] or other similar mathematical indices of shortage frequency or magnitude, because available methods [3] require a target index that is non-zero - a condition which is violated when the objective is to have no shortages. Furthermore, since about 600 initial estimates of yield were required - a number which prohibited preliminary studies to obtain good first estimates in each case, it was desirable that the optimization scheme be rapidly converging irrespective of the accuracy of the initial estimate of the yield available from a given storage.

Because there is no way of pre-determining whether an estimated yield is too large or too small, the routine would have to be efficient in either case and would also have to be developed in a way which allows collection of data necessary for subsequent estimates without prior knowledge of which conditions would prevail. Furthermore, since each trial consists of a sequential monthly routing at least 40 years long, it was apparent that the routine should not be dependent upon having the complete results of prior trials available for subsequent estimates. In other words, the routine should provide for condensation of all important aspects of a trial into as few significant parameters as possible.

The method used was proposed by Mr. Leo R. Beard and was based upon his belief that the most efficient optimization scheme would, of necessity, involve examination of the internal sequential analysis rather than a mathematical technique which used only the final results of the initial analysis to predict the yield. The method consists of computing two ratios at appropriate times during a sequential routing. The first ratio, used to estimate yield in a subsequent trial when the current estimates proves to be too small, is the ratio of the remaining storage at the end of a given month to the accumulated demand since the last time the reservoir was full. This ratio is computed each month during the sequential routing if the end-of-month storage is greater than the minimum storage. As soon as the ratio is calculated it is checked to see if it is smaller than any value previously obtained. If so, it becomes the stored value, and the corresponding month and year are also stored. Thus, at the end of a sequential routing this ratio is an indicator of the point at which an increase in yield will have the greatest effect on the storage and, also, it is an indicator of the magnitude of the change necessary to completely utilize the storage in terms of the trial demand.

Obviously, the ratio described above would be zero for one or more months if the trial yield is too large for the available storage. Consequently, a second ratio is computed for all months when the demand cannot be met. This ratio, used to estimate the yield in subsequent trials when the current estimated yield is too large, is the ratio of the accumulated shortage to the accumulated demand - both accumulations beginning at the time the reservoir was last full. In this case it is necessary to store the largest value obtained. Again, at the end of the sequential routing this ratio indicates, in terms of the estimated yield, the magnitude of reduction in yield necessary to keep from exceeding the capability of the available storage and also indicates the time when the maximum drawdown will occur.

Since both ratios contain accumulated demands, the routine is equally adaptable to both uniform and seasonally varying yields. Furthermore, since the routine does account for the state of the reservoir with respect to the demand at any point in time it was found to be sensitive to the effect of evaporation also. A few initial runs quickly indicated that the routine was capable of identifying, after the first trial routing, the ultimate critical period even though the first estimate of the yield was off by more than 100 percent and despite the fact that the critical period under the first estimate of the yield was not in the same decade as the ultimate critical period and was not of the same duration. Additional testing of the routine indicated that in most cases the correct yield could be computed without human intervention in three trials, irrespective of the error in the first estimate. Where there was no evaporation, the technique gave the correct result in two trials and, in cases where the evaporation had a major influence on the results, the routine could require as many as five trials. An example of the convergence of the routine is shown by the computer output included as Figure 1.

RESULTS

The results of this study are tabulated in Tables 2 to 8 and are illustrated in Figures 2 to 8. Although detailed analysis of the data in the tables would point out many interesting facets of the study to the engineer who is familiar with storage-yield analyses, it is more useful to point out only some of the more apparent results that are discernible to those who are not as familiar with this type of hydrologic engineering study.

First, it is apparent that seasonal variation in demand is an extremely important factor in yield analysis. At these seven sites, the analysis indicated that the seasonal variation in demand could reduce yields from 10 to 33 percent. In effect, this indicates that the assumption of uniform yield for simplified studies can result in serious over-estimates of yield when the demand is actually seasonally varying. Furthermore, it appears that the duration of the critical period is influenced by the seasonal variation in some cases. Finally, examination of the graphical data indicates that the influence of seasonal variation is not always predictable for the full range of development at a site. For this reason it would seem advisable to caution against applying a "factor" to account for this influence unless the exact nature of the influence is well-understood in the particular case.

Second, it appears from these studies that the influence of evaporation upon the yield may not be as significant as the influence of seasonal variation. Consequently, one might reason that assuming zero evaporation would be less serious than assuming no seasonal variation. However, it should be noted that the influence of such an assumption would tend to favor larger projects over small projects, because the influence of evaporation appears to be proportional to the size of the reservoir whereas the influence of seasonal variation appears to be dependent primarily upon factors such as the length of the critical period and the variations in time distribution of streamflow.

Finally, as shown on Figure 3, the combined effects of evaporation and seasonal variation in demand are apparently not always what one would expect from observing the effects of each alone. Therefore, it would appear to be advisable to carefully investigate the interrelationship between these two factors before attempting to deduce their combined effect.

CONCLUSIONS

The factors investigated in this study (as well as those described initially as being beyond the scope of this study) are of major importance in the analysis of the storage-yield relationship. This study indicates that storage requirements to meet a given yield may be underestimated by more than 40 percent if evaporation and seasonal variation are ignored when they are actually significant. Furthermore, the effects of multiple demands and complex operating rules are known to significantly alter the storage-yield relationship. However, it is difficult to devise a study to illustrate these effects because of the number of variables involved.

None of the simplified techniques known to the writer are capable of accounting for all of the factors which affect the yield in a complex multiple purpose project. Since present conditions in some areas and foreseeable future conditions in many other areas are such that these factors cannot be ignored and since multiple demands with varying priorities and attendant complex operating rules are becoming an inseparable part of even the smallest water resources developments, it appears that there is a real and ever-increasing need to emphasize the sequential routing study as the primary tool in hydrologic analyses of the storage-yield relationship.

The study described herein has demonstrated that the capability now exists to perform these sequential routings by electronic computer, even in the initial planning phases of a study. Furthermore, these routings may be used with generated streamflow data as shown by Young and Pisano [4] to establish estimates of the statistical aspects of the storage-yield relationship. Hopefully, this type of approach will gain increased acceptance as electronic computers become more widely available and as engineers become more conversant with the capabilities of the various techniques.

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TABLE 1
PERTINENT PHYSICAL AND STATISTICAL DATA
SEVEN SELECTED STATIONS

Stream	Gaging Station	Drainage Area (Sq.Mi.)	Years of Record Used	Average Annual Flow (cfs)	ANNUAL STATISTICS		RANGE OF MONTHLY STATISTICS			
					Geometric Mean	Standard Deviation	Minimum Month Geometric Mean	Maximum Month Geometric Mean	Minimum Month Standard Deviation	Maximum Month Standard Deviation
Westfield River	**Knightsville, Mass.**	162	57	315	2.489	.116	1.791	2.931	.187	.401
Arroyo Seco	**Soledad, Cal**	241	58	163	2.100	.352	-0.086	2.489	.353	.954
Deerfield River	**Charlemont, Mass.**	362	53	874	2.938	.089	2.251	3.422	.170	.396
Tygart River	**Belington, W.V.**	408	52	792	2.898	.095	2.001	3.299	.166	.621
Grand River	**Gallatin, Mo.**	2250	40	1125	2.956	.320	2.117	3.137	.526	.759
Willamette River	**Albany, Ore.**	4840	61	14,274	4.021	.108	3.534	4.410	.099	.325
Little River	**Cameron, Tex.**	7034	43	1805	3.110	.391	2.249	3.434	.438	.703

TABLE 2
RESULTS OF STORAGE-YIELD ANALYSES
WESTFIELD RIVER

USABLE STORAGE	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION - WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
(acre-feet)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)
290,000	271.6	5-61 to 9-66	272.0	5-61 to 9-66	261.9	5-61 to 9-66	261.8	5-61 to 9-66
260,000	263.8	5-61 to 9-66	264.0	5-61 to 9-66	254.2	5-61 to 9-66	254.0	5-61 to 9-66
248,000	260.6	5-61 to 9-66	260.8	5-61 to 9-66	251.3	5-61 to 9-66	251.0	5-61 to 9-66
220,000	253.3	5-61 to 9-66	253.3	5-61 to 9-66	244.2	5-61 to 9-66	244.2	5-61 to 9-66
199,000	248.0	5-61 to 9-66	248.2	5-61 to 9-66	239.1	5-61 to 9-66	238.8	5-61 to 9-66
170,000	240.4	5-61 to 9-66	240.4	5-61 to 9-66	230.1	4-64 to 9-66	228.6	5-61 to 9-66
149,000	234.9	5-61 to 2-66	234.3	4-64 to 9-66	217.0	4-64 to 11-65	215.4	4-64 to 11-65
140,000	228.7	4-64 to 2-66	227.6	4-64 to 2-66	210.1	4-64 to 11-65	208.5	4-64 to 11-65
130,000	221.0	4-64 to 1-66	219.7	4-64 to 1-66	202.4	5-64 to 11-65	200.8	5-64 to 11-65
120,000	213.0	4-64 to 1-66	211.9	4-64 to 1-66	194.2	5-64 to 11-65	192.8	5-64 to 11-65
110,000	205.1	4-64 to 1-66	204.0	4-64 to 1-66	186.1	5-64 to 11-65	184.8	5-64 to 11-65
99,000	196.5	4-64 to 1-66	195.4	4-64 to 1-66	177.2	4-64 to 11-65	175.9	4-64 to 11-65
80,000	181.5	4-64 to 1-66	180.4	4-64 to 1-66	161.6	5-64 to 10-65	160.0	5-64 to 10-65
50,000	147.5	5-64 to 1-65	146.1	5-64 to 1-65	117.2	5-64 to 11-64	115.1	5-64 to 11-64
20,000	83.5	5-64 to 11-64	81.7	5-64 to 11-64	58.9	5-64 to 11-64	57.6	5-64 to 11-64

TABLE 3
RESULTS OF STORAGE YIELD ANALYSES
ARROYO SECO

USABLE STORAGE (acre-feet)	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION - WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)
700,000*	162.7	3-17 to 1-37	153.7	3-17 to 12-35	161.7	4-17 to 12-35	152.6	4-17 to 12-35
650,000*	159.2	3-17 to 12-35	150.5	3-17 to 12-35	158.1	4-17 to 12-35	149.4	4-17 to 12-35
620,000	157.0	3-17 to 12-35	148.5	3-17 to 12-35	155.9	4-17 to 12-35	147.4	4-17 to 12-35
600,000	155.5	3-17 to 12-35	147.0	3-17 to 12-35	154.4	4-17 to 12-35	145.8	4-17 to 12-35
500,000	148.2	3-17 to 12-35	140.2	3-17 to 12-35	147.1	4-17 to 12-35	139.1	4-17 to 12-35
400,000	140.8	3-17 to 12-35	133.8	4-17 to 12-35	139.7	4-17 to 12-35	132.7	4-17 to 12-35
350,000	137.1	3-17 to 12-35	130.6	3-17 to 12-35	135.8	4-23 to 12-35	129.5	4-17 to 12-35
300,000	131.0	4-27 to 12-35	125.7	4-27 to 12-35	128.7	4-27 to 12-35	123.4	4-27 to 12-35
250,000	122.4	4-45 to 11-51	117.5	4-45 to 11-51	118.8	4-45 to 11-51	113.6	4-45 to 10-50
200,000	110.8	4-46 to 10-50	106.3	4-46 to 10-50	105.7	4-46 to 10-50	101.2	4-46 to 10-50
145,000	93.9	4-46 to 10-50	90.2	4-46 to 10-50	89.6	4-46 to 10-50	85.9	4-46 to 10-50
120,000	86.3	4-46 to 10-50	83.0	4-46 to 10-50	82.3	4-46 to 10-50	79.0	4-46 to 10-50
100,000	80.1	4-46 to 12-49	76.9	4-46 to 12-49	76.4	4-46 to 10-50	73.4	4-46 to 10-50
90,000	76.4	4-46 to 12-49	73.3	4-46 to 12-49	73.3	4-46 to 12-49	70.3	4-46 to 12-49
80,000	72.6	4-46 to 12-49	69.6	4-46 to 1-49	69.1	4-46 to 11-48	66.0	4-46 to 11-48
70,000	67.6	4-46 to 1-49	64.8	4-46 to 1-49	64.1	4-46 to 11-48	61.2	4-46 to 11-48
60,000	62.6	4-46 to 1-49	59.9	4-46 to 1-49	58.2	4-30 to 11-31	55.5	4-30 to 11-31
50,000	56.7	4-30 to 11-31	54.0	4-30 to 11-31	50.5	4-30 to 11-31	48.0	4-30 to 11-31
30,000	39.3	4-30 to 11-31	37.1	4-30 to 11-31	34.7	5-30 to 11-31	32.8	5-30 to 11-31

* With this amount of storage the yield is directly dependent upon the storage and the storage, once drawn down, cannot be completely replenished from natural streamflow.

TABLE 4
RESULTS OF STORAGE YIELD ANALYSES
DEERFIELD RIVER

USABLE STORAGE	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION - WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
(acre-feet)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)
580,000	765.8	5-61 to 9-66	765.9	5-61 to 9-66	737.8	5-61 to 10-65	736.6	5-61 to 10-65
520,000	748.6	5-61 to 2-66	748.7	5-61 to 2-66	719.8	5-61 to 10-65	718.6	5-61 to 10-65
460,000	731.0	5-61 to 2-66	731.2	5-61 to 2-66	701.9	4-64 to 10-65	698.0	4-64 to 10-65
444,000	726.5	5-61 to 2-66	725.9	5-61 to 2-66	689.0	4-64 to 10-65	685.2	4-64 to 10-65
400,000	713.6	5-61 to 2-66	713.1	5-61 to 2-66	653.8	4-64 to 10-65	650.0	4-64 to 10-65
340,000	681.6	4-64 to 2-66	679.3	4-64 to 2-66	605.8	4-64 to 10-65	602.1	4-64 to 10-65
332,000	675.5	4-64 to 2-66	673.3	4-64 to 2-66	599.3	4-64 to 10-65	595.7	4-64 to 10-65
280,000	632.2	4-64 to 9-65	628.7	4-64 to 9-65	557.7	4-64 to 10-65	554.2	4-64 to 10-65
221,000	551.7	4-64 to 3-65	549.0	4-64 to 3-65	486.4	5-64 to 11-64	481.8	5-64 to 11-64
220,000	550.2	4-64 to 3-65	547.5	4-64 to 3-65	484.5	5-64 to 11-64	479.5	5-65 to 11-64
160,000	459.9	4-64 to 3-65	457.6	4-64 to 3-65	368.7	5-64 to 11-64	364.5	5-64 to 11-64
112,000	381.0	5-64 to 3-65	379.4	5-64 to 3-65	275.2	5-64 to 11-64	271.7	5-64 to 11-64
100,000	357.3	5-64 to 11-64	352.9	5-64 to 11-64	251.8	5-64 to 11-64	248.6	5-64 to 11-64
40,000	192.0	5-64 to 11-64	189.3	5-64 to 11-64	128.3	5-64 to 10-64	125.6	5-64 to 10-64

TABLE 5
RESULTS OF STORAGE-YIELD ANALYSES
TYGART RIVER

USABLE STORAGE	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION - WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
(acre-feet)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)
450,000	739.5	4-39 to 7-42	740.1	4-39 to 7-42	684.4	5-29 to 11-31	684.7	5-29 to 11-31
400,000	714.4	5-29 to 11-31	715.1	5-29 to 11-31	656.8	4-30 to 11-31	655.9	4-30 to 11-31
380,000	703.2	5-29 to 11-31	703.8	5-29 to 11-31	641.2	4-30 to 11-31	640.2	4-30 to 11-31
360,000	692.2	5-29 to 11-31	692.8	5-29 to 11-31	625.6	4-30 to 11-31	624.6	4-30 to 11-31
350,000	686.7	5-29 to 11-31	687.4	5-29 to 11-31	617.8	4-30 to 11-31	616.7	4-30 to 11-31
340,000	681.2	5-29 to 11-31	681.9	5-29 to 11-31	610.1	4-30 to 11-31	609.0	4-30 to 11-31
320,000	668.4	4-30 to 11-31	667.6	4-30 to 11-31	589.2	4-30 to 12-30	587.5	4-30 to 12-30
300,000	650.9	4-30 to 11-31	650.0	4-30 to 11-31	555.7	4-30 to 12-30	554.1	4-30 to 12-30
250,000	572.2	4-30 to 1-31	571.2	4-30 to 1-31	471.4	4-30 to 12-30	470.0	4-30 to 12-30
220,000	516.7	4-30 to 12-30	515.2	4-30 to 12-30	421.4	4-30 to 12-30	420.2	4-30 to 12-30
190,000	455.1	4-30 to 12-30	453.9	4-30 to 12-30	370.9	4-30 to 12-30	369.8	4-30 to 12-30
160,000	393.2	4-30 to 12-30	392.2	4-30 to 12-30	320.7	4-30 to 12-30	319.8	4-30 to 12-30
130,000	331.5	4-30 to 12-30	330.7	4-30 to 12-30	270.4	4-30 to 12-30	269.6	4-30 to 12-30
100,000	269.8	4-30 to 12-30	269.1	4-30 to 12-30	215.4	5-30 to 11-30	214.7	5-30 to 11-30
80,000	228.7	4-30 to 12-30	228.0	4-30 to 12-30	176.4	5-30 to 11-30	175.9	5-30 to 11-30
60,000	184.7	5-30 to 12-30	184.4	5-30 to 12-30	137.4	6-30 to 11-30	137.1	6-30 to 11-30
40,000	135.4	6-30 to 12-30	135.5	6-30 to 12-30	93.0	6-30 to 11-30	92.9	6-30 to 11-30
20,000	72.4	6-30 to 11-30	72.3	6-30 to 11-30	48.6	6-30 to 11-30	48.6	6-30 to 11-30
10,000	39.4	6-30 to 11-30	39.4	6-30 to 11-30	26.5	6-30 to 11-30	26.5	6-30 to 11-30

TABLE 6
RESULTS OF STORAGE-YIELD ANALYSES
GRAND RIVER

USABLE STORAGE	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION -WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
acre-feet	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)
2,500,000	919.9	8-32 to 5-41	871.9	6-32 to 5-41	903.7	6-32 to 9-41	855.2	6-32 to 9-41
2,300,000	888.2	8-32 to 5-41	842.7	6-32 to 5-41	874.6	6-32 to 9-41	827.8	6-32 to 9-41
2,400,000	904.0	8-32 to 5-41	857.9	6-32 to 5-41	889.1	6-32 to 9-41	841.6	6-32 to 9-41
2,200,000	872.1	8-32 to 5-41	828.6	6-32 to 5-41	859.9	6-32 to 9-41	814.5	6-32 to 9-41
2,000,000	838.6	6-52 to 4-58	798.9	6-52 to 4-58	826.5	6-52 to 1-58	785.7	6-52 to 1-58
1,500,000	720.0	6-52 to 4-58	685.3	6-52 to 1-58	705.4	6-52 to 1-58	670.3	6-52 to 1-58
1,000,000	597.4	6-52 to 1-58	567.6	6-52 to 1-58	583.9	6-52 to 1-58	555.0	6-52 to 1-58
800,000	547.8	6-52 to 1-58	520.2	6-52 to 1-58	535.6	6-53 to 1-58	508.7	6-52 to 1-58
700,000	513.2	7-37 to 5-41	493.4	7-37 to 5-41	506.3	6-53 to 1-58	480.9	6-53 to 1-58
600,000	477.7	7-37 to 5-41	458.2	7-37 to 5-41	475.1	7-37 to 12-40	452.8	6-53 to 1-58
400,000	405.2	7-37 to 5-41	388.3	7-37 to 5-41	396.9	7-37 to 12-40	378.1	7-37 to 12-40
300,000	351.0	7-37 to 2-39	336.7	7-37 to 2-39	345.8	7-37 to 2-39	331.3	7-37 to 2-39
200,000	263.6	7-37 to 2-39	250.4	7-37 to 2-39	259.7	7-37 to 2-39	246.6	7-37 to 2-39
100,000	176.3	7-37 to 2-39	164.2	7-37 to 2-39	173.6	7-37 to 2-39	161.6	7-37 to 2-39
80,000	152.8	7-55 to 5-56	145.4	7-55 to 5-56	156.3	7-37 to 2-39	144.6	7-37 to 2-39
60,000	119.8	7-55 to 5-56	112.3	7-55 to 5-56	128.3	7-55 to 5-56	120.3	6-53 to 3-54
50,000	103.1	7-55 to 5-56	95.8	7-55 to 5-56	110.5	7-55 to 5-56	102.7	7-55 to 5-56
30,000	70.0	7-55 to 5-56	62.8	7-55 to 5-56	75.0	7-55 to 5-56	65.6	6-53 to 1-54
15,000	45.1	7-55 to 5-56	38.1	7-55 to 5-56	48.4	7-55 to 5-56	32.1	6-53 to 10-53

TABLE 7
RESULTS OF STORAGE YIELD ANALYSES
WILLAMETTE RIVER

USABLE STORAGE	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION - WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
(acre-feet)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year	Yield (cfs)	Critical Period (month & year)
5,800,000	10,814	5-28 to 10-31	10,805	5-28 to 10-31	10,120	5-28 to 10-31	10,111	5-28 to 10-31
5,400,000	10,652	5-28 to 10-31	10,644	5-28 to 10-31	9,968	5-28 to 10-31	9,958	5-28 to 10-31
5,000,000	10,491	5-28 to 10-31	10,482	5-28 to 10-31	9,817	5-28 to 10-31	9,808	5-28 to 10-31
4,600,000	10,329	5-28 to 10-31	10,321	5-28 to 10-31	9,509	4-40 to 10-41	9,496	4-40 to 10-41
4,200,000	10,168	5-28 to 10-31	10,161	5-28 to 10-31	9,191	4-40 to 10-41	9,178	4-40 to 10-41
3,800,000	10,004	5-28 to 10-31	9,997	5-28 to 10-31	8,857	5-40 to 10-41	8,847	5-40 to 10-41
3,400,000	9,793	4-40 to 10-41	9,784	4-40 to 10-41	8,523	5-40 to 10-41	8,513	5-40 to 10-41
3,000,000	9,429	4-40 to 10-41	9,420	4-40 to 10-41	8,073	5-40 to 10-40	8,053	5-40 to 10-40
2,800,000	9.245	4-40 to 10-41	9,237	4-40 to 10-41	7,650	5-40 to 10-40	7,630	5-40 to 10-40
2,400,000	8,876	4-40 to 10-41	8,869	4-40 to 10-41	6,804	5-40 to 10-40	6,787	5-40 to 10-40
1,900,000	8,223	5-44 to 12-44	8,208	5-44 to 12-44	5,747	5-40 to 10-40	5,732	5-40 to 10-40
1,440,000	7,137	5-44 to 12-44	7,125	5-44 to 12-44	4,766	5-40 to 10-40	4,756	5-40 to 10-40
900,000	5,651	5-40 to 10-40	5,635	5-40 to 10-40	3,627	5-40 to 10-40	3,614	5-40 to 10-40
700,000	4,989	5-40 to 10-40	4,975	5-40 to 10-40	3,165	6-40 to 10-40	3,156	6-40 to 10-40
500,000	4,330	5-40 to 10-40	4,318	5-40 to 10-40	2,676	6-40 to 10-40	2,669	6-40 to 10-40
300,000	3,658	6-40 to 10-40	3,648	6-40 to 10-40	2,185	6-40 to 10-40	2,179	6-40 to 10-40
100,000	2,837	6-40 to 10-40	2,830	6-40 to 10-40	1,628	6-40 to 9-40	1,622	6-40 to 9-40
50,000	2,580	6-40 to 9-40	2,572	6-40 to 9-40	1,450	7-40 to 9-40	1,446	7-40 to 9-40
20,000	2,356	7-40 to 9-40	2,349	7-40 to 9-40	1,233	7-40 to 8-40	1,229	7-40 to 8-40

TABLE 8
RESULTS OF STORAGE-YIELD ANALYSES
LITTLE RIVER

USABLE STORAGE	WITHOUT EVAPORATION OR SEASONAL VARIATION		WITH EVAPORATION - WITHOUT SEASONAL VARIATION		WITHOUT EVAPORATION - WITH SEASONAL VARIATION		WITH EVAPORATION & SEASONAL VARIATION	
(acre-feet)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)	Yield (cfs)	Critical Period (month & year)
6,500,000*	1382.8	5-47 to 3-57	1240.4	5-47 to 3-57	1377.4	5-47 to 3-57	1237.0	5-47 to 3-57
6,000,000*	1312.1	5-47 to 3-57	1175.8	5-47 to 3-57	1307.2	5-47 to 3-57	1172.6	5-47 to 3-57
5,500,000	1241.8	5-47 to 3-57	1111.4	5-47 to 3-57	1237.4	5-47 to 3-57	1108.4	5-47 to 3-57
5,000,000	1171.5	5-47 to 3-57	1047.4	5-47 to 3-57	1167.5	5-47 to 3-57	1044.6	5-47 to 3-57
4,500,000	1101.8	5-47 to 3-57	983.7	5-47 to 3-57	1097.5	5-47 to 3-57	981.1	5-47 to 3-57
4,000,000	1031.6	5-47 to 3-57	920.3	5-47 to 3-57	1027.8	5-47 to 3-57	917.8	5-47 to 2-57
3,500,000	961.1	5-47 to 3-57	856.8	5-47 to 3-57	957.4	5-47 to 2-57	854.2	5-47 to 2-57
3,000,000	891.1	5-47 to 3-57	793.4	5-47 to 3-57	887.7	5-47 to 2-57	790.7	5-47 to 2-57
2,500,000	820.7	6-47 to 3-57	729.9	5-47 to 3-57	816.9	5-47 to 2-57	727.0	5-47 to 10-56
1,500,000	679.0	6-47 to 3-57	605.0	6-47 to 3-57	673.9	6-49 to 10-56	599.6	6-47 to 10-56
1,200,000	626.4	6-49 to 3-57	562.1	6-49 to 3-57	619.1	6-49 to 10-56	553.8	6-49 to 10-56
1,000,000	590.9	6-49 to 3-57	530.5	6-49 to 3-57	582.5	6-49 to 10-56	520.8	6-49 to 10-56
750,000	546.4	6-49 to 3-57	491.2	6-49 to 3-57	537.0	6-49 to 10-56	480.4	6-49 to 10-56
500,000	466.9	12-53 to 2-57	421.1	12-53 to 2-57	462.5	12-53 to 10-56	411.7	12-53 to 10-56
300,000	375.9	12-53 to 10-56	330.3	12-53 to 10-56	366.4	1-54 to 10-56	320.2	1-54 to 10-56
200,000	321.8	9-50 to 3-52	283.7	12-53 to 10-56	318.2	1-54 to 10-56	274.3	1-54 to 10-56
100,000	224.8	12-53 to 1-55	187.2	1-54 to 1-55	216.2	5-54 to 1-55	175.1	5-54 to 10-54
50,000	133.8	6-51 to 3-52	98.3	6-51 to 3-52	113.2	5-54 to 10-54	70.7	5-54 to 10-54

* With this amount of storage the yield is directly dependent upon the storage and the storage, once drawn down, cannot be completely replenished from natural streamflow.

```
GRAND AVERAGE

      CFS        END OF MONTH STORAGE IN AC-FT     AC-FT      CFS TO PIPELINE
PER  INFLOW      MIN    BUFFER    ACTUAL        MAX      EVAP     REQ ACTUAL   SHRTG
YR   14274    100000                        3500000       -53       0       0       0

SHORTAGE INDEX, PIPELINE  0.      OUTLET    .197  DOWNSTREAM  0.      POWER   0.

TRIAL NO.  1 TRIAL YIELD IS   10999.9
BEGINNING OF CRITICAL PERIOD IS  5-1928
TIME OF MAXIMUM DRAWDOWN IS 10-1931
MINIMUM STORAGE IS    100000
NEXT TRIAL YIELD IS 9836.87


GRAND AVERAGE

      CFS        END OF MONTH STORAGE IN AC-FT     AC-FT      CFS TO PIPELINE
PER  INFLOW      MIN    BUFFER    ACTUAL        MAX      EVAP     REQ ACTUAL   SHRTG
YR   14274    100000                        3500000      -614       0       0       0

SHORTAGE INDEX, PIPELINE  0.      OUTLET    .000  DOWNSTREAM  0.      POWER   0.

TRIAL NO.  2 TRIAL YIELD IS    9836.9
BEGINNING OF CRITICAL PERIOD IS  4-1940
TIME OF MAXIMUM DRAWDOWN IS 10-1941
MINIMUM STORAGE IS    100000
NEXT TRIAL YIELD IS 9783.50


GRAND AVERAGE

      CFS        END OF MONTH STORAGE IN AC-FT     AC-FT      CFS TO PIPELINE
PER  INFLOW      MIN    BUFFER    ACTUAL        MAX      EVAP     REQ ACTUAL   SHRTG
YR   14274    100000                        3500000      -650       0       0       0

SHORTAGE INDEX, PIPELINE  0.      OUTLET    .000  DOWNSTREAM  0.      POWER   0.

TRIAL NO.  3 TRIAL YIELD IS    9783.5
BEGINNING OF CRITICAL PERIOD IS  4-1940
TIME OF MAXIMUM DRAWDOWN IS 10-1941
MINIMUM STORAGE IS    100000
```

FIGURE 1

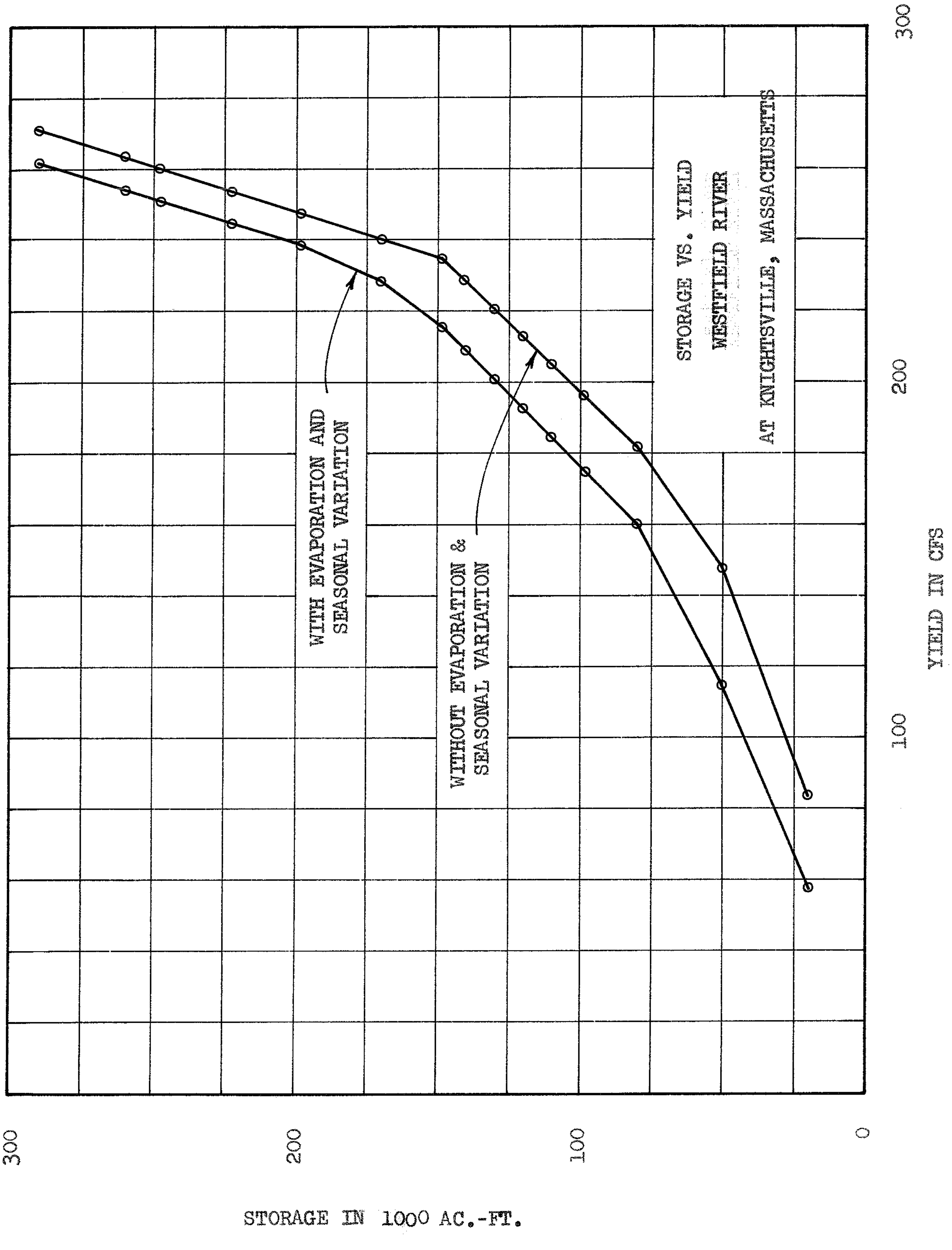
STORAGE VS. YIELD
WESTFIELD RIVER
AT KNIGHTSVILLE, MASSACHUSETTS
WITH EVAPORATION AND SEASONAL VARIATION
WITHOUT EVAPORATION & SEASONAL VARIATION
YIELD IN CFS
100
200
300
STORAGE IN 1000 AC.-FT.
0
100
200
300

FIGURE 2

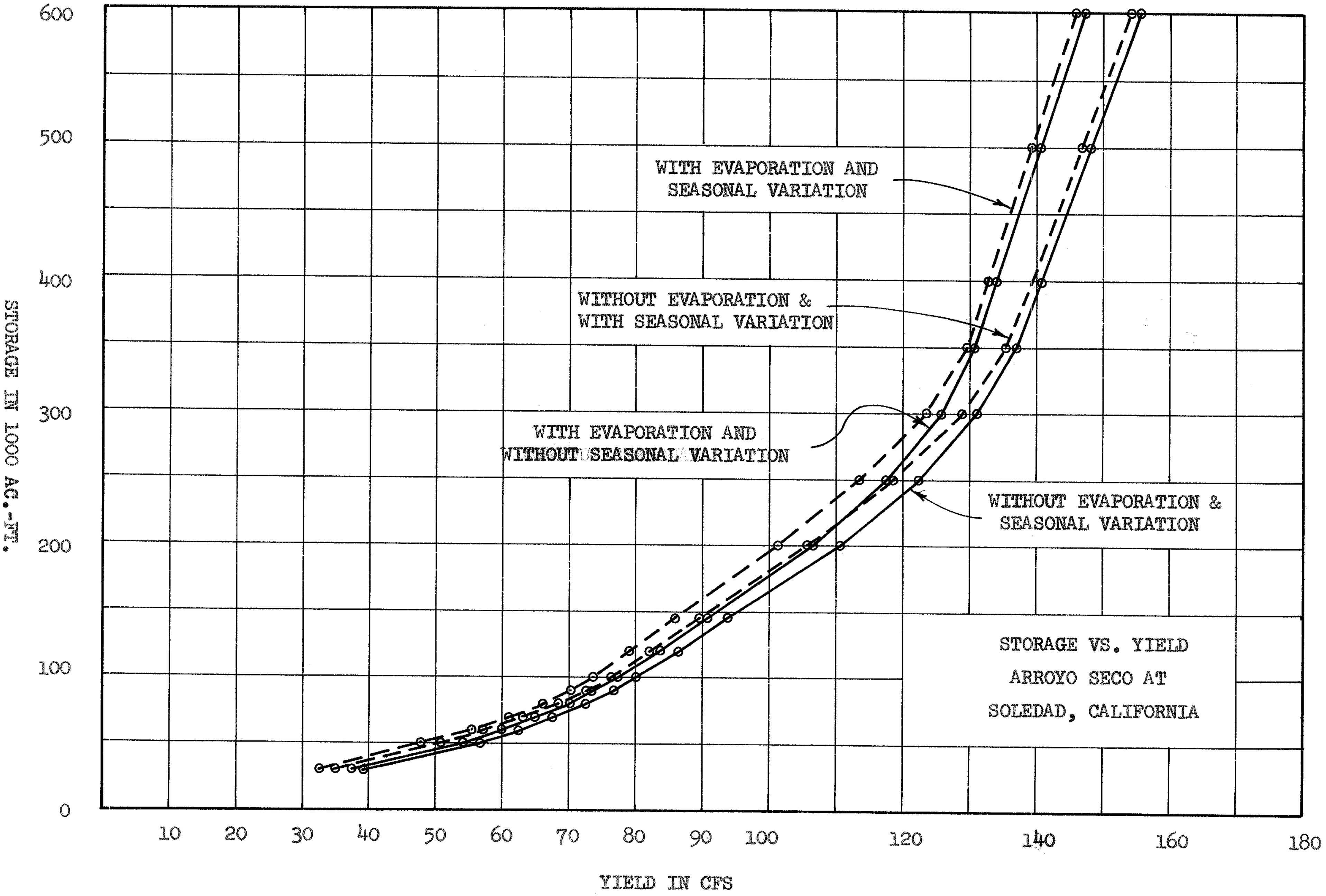
STORAGE VS. YIELD
ARROYO SECO AT
SOLEDAD, CALIFORNIA
WITH EVAPORATION AND SEASONAL VARIATION
WITHOUT EVAPORATION & WITH SEASONAL VARIATION
WITH EVAPORATION AND WITHOUT SEASONAL VARIATION
WITHOUT EVAPORATION & SEASONAL VARIATION
STORAGE IN 1000 AC.-FT.
0
100
200
300
400
500
600
YIELD IN CFS
10
20
30
40
50
60
70
80
90
100
120
140
160
180

FIGURE 3

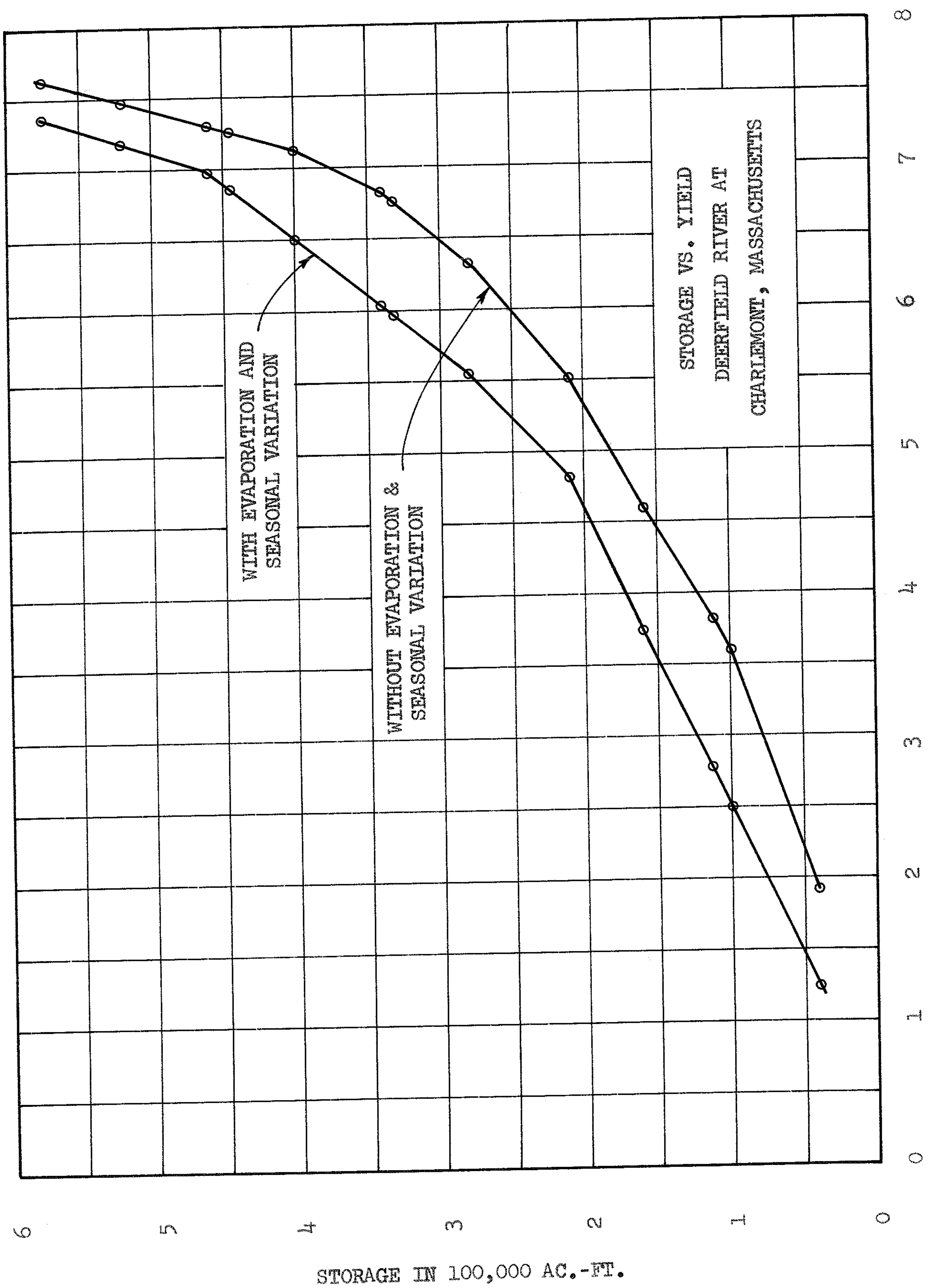
STORAGE VS. YIELD
DEERFIELD RIVER AT
CHARLEMONT, MASSACHUSETTS
WITH EVAPORATION AND
SEASONAL VARIATION
WITHOUT EVAPORATION &
SEASONAL VARIATION
YIELD IN 100 CFS
0
1
2
3
4
5
6
7
8
STORAGE IN 100,000 AC.-FT.
0
1
2
3
4
5
6

FIGURE 4

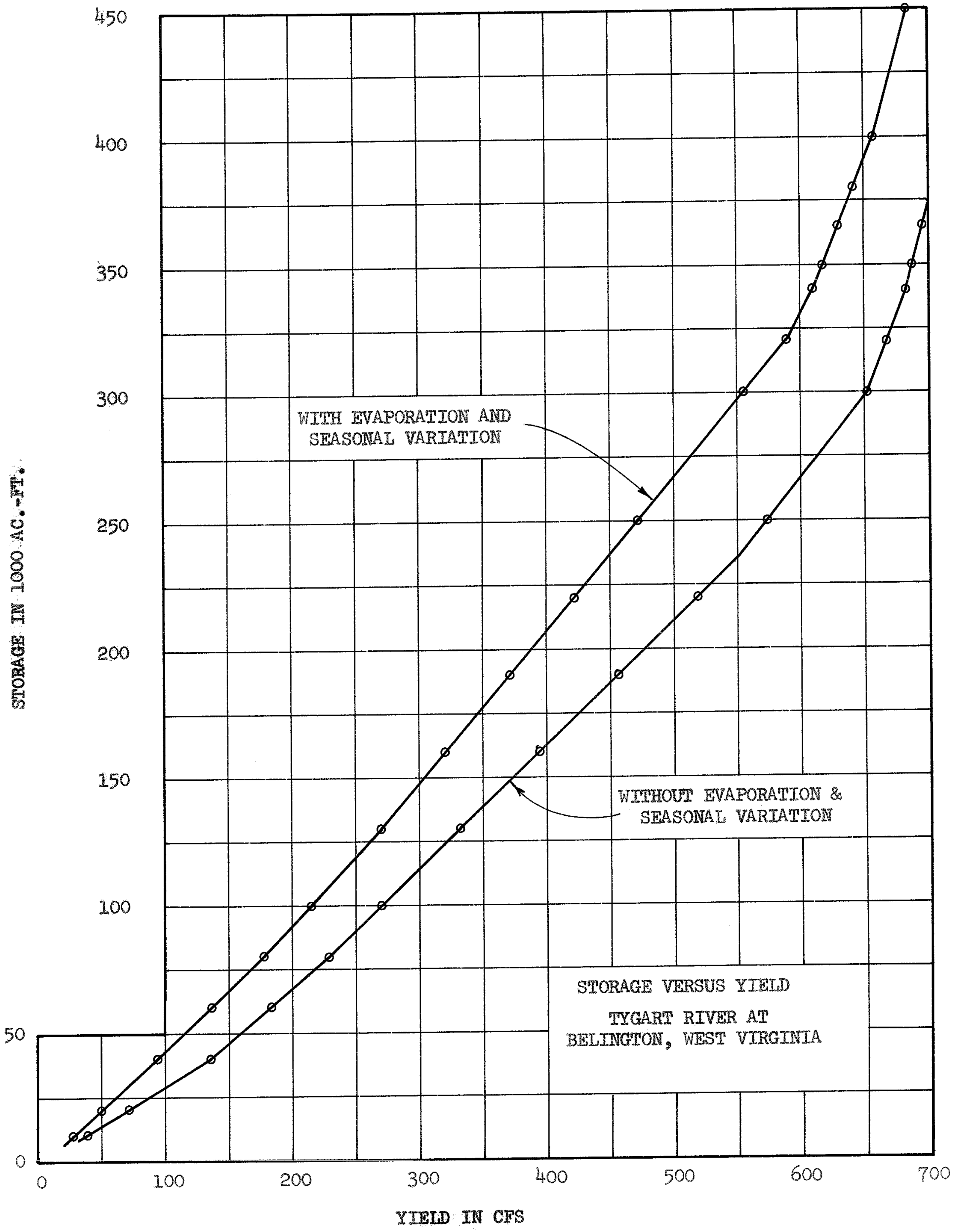
450
400
350
300
250
200
150
100
50
0
STORAGE IN 1000 AC.-FT.
0
100
200
300
400
500
600
700
YIELD IN CFS
WITH EVAPORATION AND SEASONAL VARIATION
WITHOUT EVAPORATION & SEASONAL VARIATION
STORAGE VERSUS YIELD
TYGART RIVER AT BELINGTON, WEST VIRGINIA

FIGURE 5

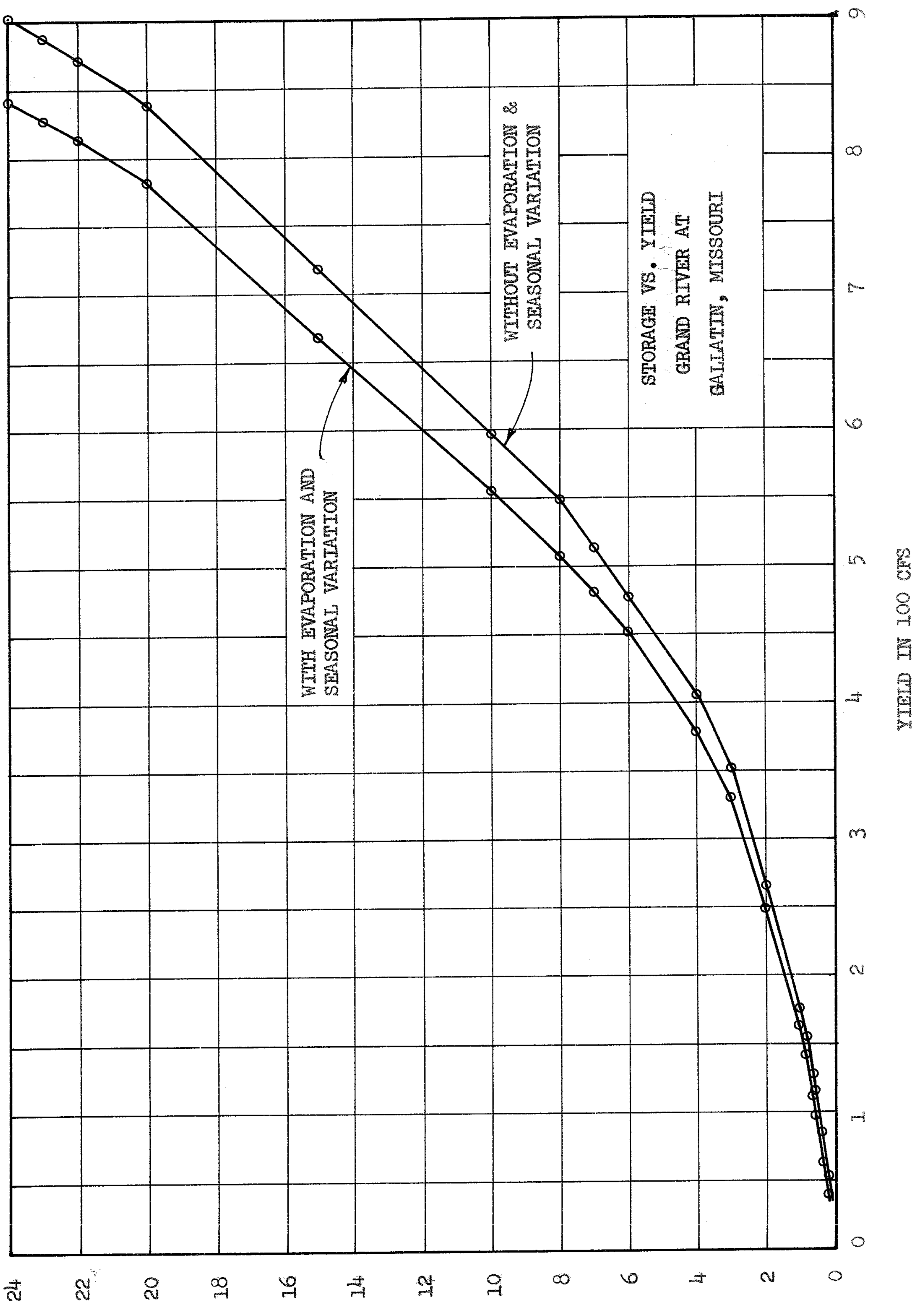
STORAGE VS. YIELD
GRAND RIVER AT
GALLATIN, MISSOURI
WITHOUT EVAPORATION &
SEASONAL VARIATION
WITH EVAPORATION AND
SEASONAL VARIATION
YIELD IN 100 CFS
0
1
2
3
4
5
6
7
8
9
0
2
4
6
8
10
12
14
16
18
20
22
24
STORAGE IN 100,000 AC.-FT.

FIGURE 6

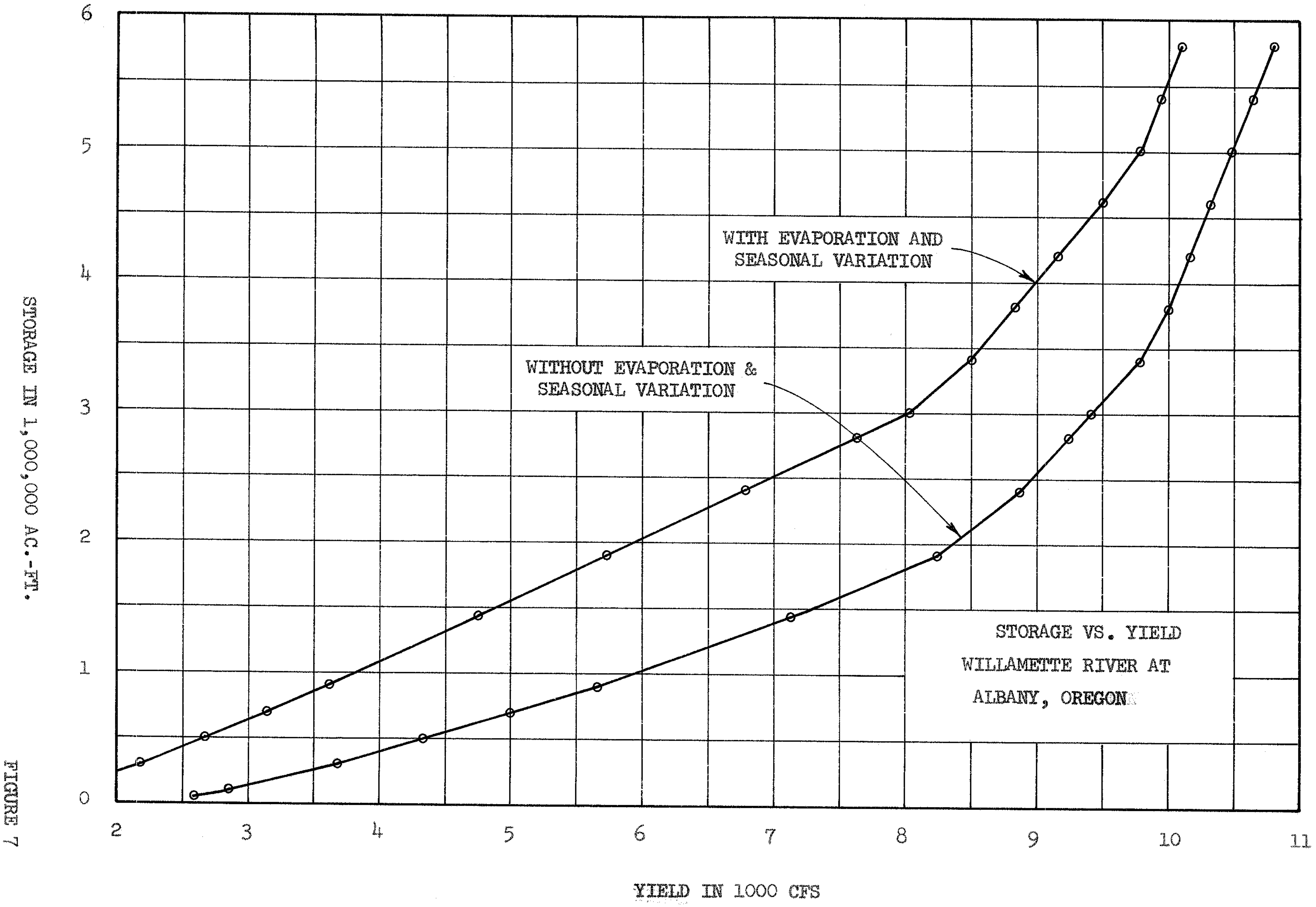
STORAGE VS. YIELD
WILLAMETTE RIVER AT
ALBANY, OREGON
WITH EVAPORATION AND
SEASONAL VARIATION
WITHOUT EVAPORATION &
SEASONAL VARIATION
STORAGE IN 1,000,000 AC.-FT.
0
1
2
3
4
5
6
YIELD IN 1000 CFS
2
3
4
5
6
7
8
9
10
11

FIGURE 7

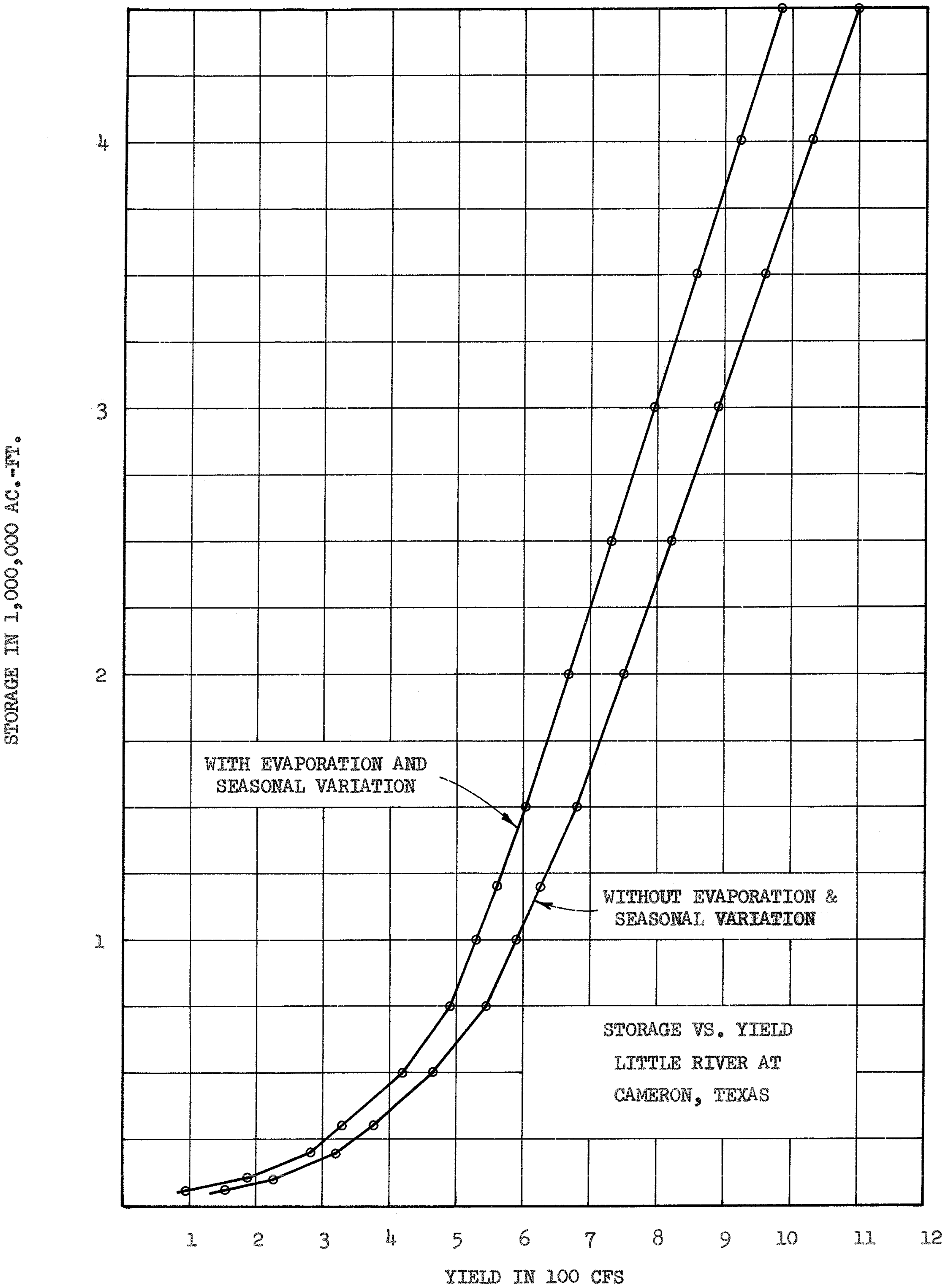
STORAGE IN 1,000,000 AC.-FT.
4
3
2
1
1
2
3
4
5
6
7
8
9
10
11
12
YIELD IN 100 CFS
WITH EVAPORATION AND SEASONAL VARIATION
WITHOUT EVAPORATION & SEASONAL VARIATION
STORAGE VS. YIELD
LITTLE RIVER AT
CAMERON, TEXAS

FIGURE 8

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TP-62	Flood Hydrograph and Peak Flow Frequency Analysis
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