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The characteristics of droughts that determine their severity and the regulatory measures required to provide protection against droughts depend to a large extent on the basic characteristics of meteorological and hydrological phenomena and to a large extent on the nature of operations that are affected by droughts. In irrigation applications, for example, severe droughts that occur during the non-irrigation seasons may be of minor significance, whereas moderate droughts during the irrigation seasons might be of critical consequences. Where the use of water is only a small fraction of the supply, long-duration droughts might be of minor consequences, whereas severe short-duration droughts could be critical. On the other hand, where use of water is high, long periods of carry over are necessary and short-duration droughts might not be critical. This paper examines the effects of droughts from the standpoint of differences in streamflow characteristics and differences in development and use. Particular attention is given to the regulatory requirements of reservoirs in relation to these factors.

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TP-30

DROUGHT SEVERITY AND WATER SUPPLY DEPENDABILITY

by

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INTRODUCTION

The characteristics of droughts that determine their severity and the regulatory measures required to provide protection against droughts depend to a large extent on the basic characteristics of meteorological and hydrological phenomena and to a large extent on the nature of operations that are affected by droughts. In irrigation applications, for example, severe droughts that occur during the nonirrigation seasons may be of minor significance, whereas moderate droughts during the irrigation seasons might be of critical consequences. Where the use of water is only a small fraction of the supply, long-duration droughts might be of minor consequences, whereas severe short-duration droughts could be critical. On the other hand, where use of water is high, long periods of carryover are necessary and short-duration droughts might not be critical. It is the purpose of this paper to examine the effects of droughts from the standpoint of differences in streamflow characteristics and differences in development and use. Particular attention is given to the regulatory requirements of reservoirs in relation to these factors.

One of the problems in reservoir regulation of streamflows concerns the development of operation rules. Usually, the operation consists of providing the required services to the maximum extent feasible, declaring some surpluses

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when it appears that water might otherwise be wasted, and declaring some shortages when it appears that supplies might be depleted. Such operation criteria have usually been highly arbitrary. In an attempt to assess the value of a flexible operation rule, a study has been included to determine the difference in yield obtainable with rigid and flexible operation rules.

Perhaps the greatest uncertainty in planning reservoirs for drought regulation is the uncertainty of the representativeness of historical droughts as an indicator of future drought potential. In order to indicate the degree of uncertainty of these estimates, stochastic procedures are used to compare drought severity in different sequences having the same fundamental streamflow characteristics. The same technique is used for examining the relative severity of short-duration and long-duration droughts that occur in any particular period of record.

The general procedure used for conducting this experiment consists of selecting two streams with relatively long records of unimpaired flows, one stream characterized by relatively stable flows and one by highly variable flows. The statistical characteristics of the two flow sequences were analyzed for developing streamflow generation models, and 500-year periods of flows were generated for each stream. It is considered that these two long streamflow sequences can well represent flows that might actually occur over a 500-year period with unchanging conditions. Although it is not contended that the modeling process perfectly represents flows at the selected stream gaging stations, it is felt that the long sequences sufficiently represent realistic streamflow conditions at arbitrary locations for use in the experiment described herein.

Each of the 500-year sequences was divided into ten 50-year sequences, and studies of drought severity and storage requirements for each of these sequences were made and compared with each other and to the corresponding quantities for the 500-year sequence. Storage determinations were made for uniform yield of various magnitudes and for seasonal varying yields, both in phase with runoff and out of phase with runoff. Comparison of ranges in storage requirements or obtainable yields are intended to reflect the degree of uncertainty involved in reservoir design and the effects of seasonal variations of demand. Also, a flexible operation rule is tested to evaluate the additional yield that might be obtained with such a rule.

STUDY PROCEDURE

The two streams selected and their characteristics are shown in Table 1. For each stream, 500 years of synthetic monthly streamflow values were generated by use of the model described in reference USACE 1966b, which is essentially a first-order Markov chain with seasonally varying frequency and correlation parameters.

TABLE 1.

STATISTICS OF ANNUAL STREAMFLOWS

STREAM	DRAINAGE AREA sq. mi	AVERAGE YIELD (cfs)	GEOMETRIC MEAN cfs	GEOMETRIC MEAN log	STANDARD DEVIATION OF LOGS
Arroyo Seco near Soledad, CA	241	174	132	2.120	.352
Willamette River at Albany, OR	4,840	14,300	14,000	4.147	.108

As a preliminary examination of variations in drought severity, the most severe drought in terms of low flow for a specified duration was determined for each 50 years of each 500-year sequence. Typical results of this study are illustrated in Table 2. Results show great variation in relative severity of droughts of different durations. For example, the order of severity of the worst drought in the seventh 50-year period is 6, 1, 2 and 9 for the four durations illustrated. While that period contains the worst 18-month drought, it has only the ninth worst of the ten 54-month droughts.

For each stream, the storages required to produce uniform yields of 30, 50, 70 and 85 percent of the long-term average flow, without experiencing any shortage within the 500 years, were determined. Then storages required to produce the same yields without shortages in each 50 years of each 500-year sequence were determined. Reservoirs were assumed 50 percent full at the start and, in the case of the 50-year studies, the entire flow sequence was repeated once in order to eliminate any bias introduced by this assumption. In essentially all of the 8 cases (2 streams and 4 yields each), one of the 10 storages thus determined equaled the storage determined for the corresponding 500-year period, because the same critical drought period controlled both determinations. However, determinations based on other 50-year periods were substantially different, as described below.

In order not to mask the variations in storage requirement due to the factors studied, net evaporation was assumed to be zero in these studies. The sensitivity of storage requirements to evaporation has been studied by Moss and Dawdy (1971) and Fredrich (1969).

TABLE 2

MINIMUM VOLUMES OF 50-YEAR SAMPLES
ARROYO SECO

Volumes for Selected Drought Durations in cfs-months

	6-Month		18-Month		30-Month		54-Month	
Rank	Sample	Volume	Sample	Volume	Sample	Volume	Sample	Volume
1	6	2	7	221	6	695	2	2118
2	10	2	6	254	7	873	5	2855
3	4	4	10	274	10	949	9	2942
4	5	5	1	302	2	953	6	3150
5	8	5	5	337	5	1123	10	3470
6	7	7	3	403	4	1293	4	3665
7	1	7	2	450	9	1332	3	3704
8	2	7	9	502	3	1345	1	3718
9	9	7	4	531	1	1411	7	3885
10	3	9	8	562	8	1424	8	3904

TABLE 3

HYPOTHETICAL SEASONAL VARIATION OF DEMAND
IN RELATION TO RUNOFF

Month	Runoff ratio to annual		Demand ratio to annual	
	Arroyo Seco	Willamette	In-phase	Out-of-phase
Oct	.08	.35	.85	1.00
Nov	.26	1.04	1.00	.85
Dec	1.10	1.61	1.15	.75
Jan	2.08-	2.04	1.25	.70
Feb	3.72	1.90	1.30	.75
Mar	2.50	1.44	1.25	.85
Apr	1.50	1.20	1.15	1.00
May	.53	.90	1.00	1.15
Jun	.22+	.68	.85	1.25
Jul	.08	.38	.75	1.30
Aug	.05	.25	.70	1.25
Sep	.05	.25	.75	1.15

In order to measure to some degree the impact of seasonal variation in use, two approximately sinusoidal patterns of use were employed--one in phase with the seasonal runoff pattern and one out of phase, as shown in Table 3. Storage determinations for each of the 50-year periods on each stream and for each average yield without shortages were then made for each of the 50-year periods for each stream, and were compared with corresponding storages for uniform yields.

In order to obtain an indication of advantages to be gained by some flexibility in use, a varying use schedule was tested. The schedule varies from a constant target as much as 20 percent above and below that target, in proportion to the square of the storage departure from a seasonally varying storage rule curve. The rule curve was defined as follows:

a. From the 50-year operation studies based on constant yield, select all drawdown periods where more than 80 percent of the storage capacity was withdrawn.

b. The maximum storage for each calendar month within these periods was tabulated for each 50-year sequence.

c. For each calendar month, the median of the 10 values obtained in "b" was selected for the rule curve.

The target yield used to develop the varying use schedule was adjusted to cause full use of reservoir storage during each 50-year period.

RESULTS

Storage with Constant Demands.

The ratio of the 500-year storage requirement to the average annual flow on the two streams is noteworthy. The storage requirement to supply 50 percent of the average yield on the Arroyo Seco is 1.45 times the average annual flow while for the same level of demand, storage required on the Willamette is only 0.22 of the average annual flow. As the level of development increases, the storage requirement increases rapidly. For the 85 percent yield the storage requirement represents 5.56 times and .88 times the average annual flow for the Arroyo Seco and Willamette respectively.

The results for the constant-demand operation study show that the drought period which established the long-term storage requirement was nearly always wholly within one of the 50-year samples. Therefore, one 50-year period required the same storage regulation as did the 500-year period and the remaining nine samples required lesser storage than the 500-year requirement. Only in one case (85 percent yield at Arroyo Seco) did a sample require more storage. This was caused by drought periods at both ends of the 50-year sample and the recycling of the sample to eliminate the bias due to starting storage created a drought more severe than the existing critical drought in the 500-year sample.

Figures 1 and 2 illustrate the differences in constant-demand storage requirement estimates based on different streamflow sequences. Although the amount of storage required differs greatly in relation to average annual flow at the two streams studied (as described above), the variability of storage estimates in relation to the long-term requirement at each location is not greatly different. Ranges obtained are as follows:

TABLE 4.

RANGE OF ESTIMATES OF REQUIRED STORAGES

YIELD	WILLAMETTE	ARROYO SECO
30%	.53-1.0	.46-1.0
50%	.61-1.0	.44-1.0
70%	.60-1.0	.46-1.0
85%	.56-1.0	.57-1.0
Avg.	.58-1.0	.48-1.0

Storage with Seasonal Demands.

The results of the in-phase and out-of-phase demand rates are shown in Table 5 and Figures 1 and 2. The cumulative frequency of the storage requirements has been expressed as a ratio of the long-term storage requirement for the Arroyo Seco and Willamette with a demand rate equivalent to 50 percent of average yield. The storage requirements for yields with different phase angles do not differ very significantly for the Arroyo Seco, while there is large difference for the Willamette. This is caused by the difference in variability of the streams. The storage requirement of a given sample for the Arroyo Seco is determined by cumulative flow deficiencies for several years; therefore, the within-year variation of demand is not very significant. On the other hand, the storage requirements for the Willamette River are set by the cumulative deficiencies within a given year. Therefore, the storage requirement in this case is very sensitive to the demand schedule.

Flexible Operation Rule.

For each stream and each level of demand, a rule curve was derived as described in the preceding section and was applied to all 50-year sequences in terms of the ratio of rule-curve storage to usable storage capacity. Monthly ratios obtained ranged from .50 to .65 for Arroyo Seco and from .22 to .70 for Willamette River. Usable storage capacity for each 50-year sequence is that derived for the constant demand in each of the 80 cases (2 streams, 4 demand levels and 10 sequences).

Two operation rules were investigated. One provides surplus water when storage exceeds the operation-rule storage, and the other does not. In both, shortages (up to 20 percent) are declared when the storage is below rule-curve

TABLE 5

STORAGE REQUIREMENTS FOR WILLAMETTE RIVER AND ARROYO SECO

Starting Year	Storage Requirements in 1000 acre feet for yields of											
	30%			50%			70%			85%		
	In-Phase	Constant	Out-of-Phase	In-Phase	Constant	Out-of-Phase	In-Phase	Constant	Out-of-Phase	In-Phase	Constant	Out-of-Phase
Willamette												
1	408.4	558.2	635.4	1262.9	1616.6	1854.6	2376.4	2980.5	3345.4	6880.3	7334.7	7918.0
51	381.8	661.5	946.9	1235.6	1719.9	2197.7	2624.8	3180.3	3714.7	5303.9	5934.3	6458.0
101	714.2	754.4	961.5	2015.6	1807.1	2153.8	3456.3	2911.8	3484.9	5326.1	5098.2	5759.8
151	483.0	679.4	820.1	1491.6	1910.4	2146.0	3482.8	4177.9	4841.3	6570.1	7473.1	8281.8
201	381.4	595.8	838.3	1219.6	1573.2	1884.2	2775.8	3494.1	4053.4	8128.2	9116.8	9812.7
251	370.7	555.0	638.4	1259.7	1629.0	1864.6	2340.3	2927.9	3476.5	6045.9	7032.9	7730.3
301	260.2	510.8	654.4	971.2	1432.6	1810.9	2443.4	2943.5	3591.0	6781.2	7740.8	8438.5
351	256.1	545.1	791.1	1012.7	1497.0	1974.8	1939.3	2518.9	3182.5	5056.3	5798.2	6308.8
401	248.4	454.9	649.7	891.1	1370.7	1848.5	2538.3	3234.8	3816.6	5843.9	6643.0	7451.9
451	604.0	854.0	1024.3	1833.6	2253.0	2554.4	3432.2	4102.5	4765.8	6536.1	7411.0	8108.2
Long Term		854.0			2253.0			4177.9			9117.0	
Arroyo Seco												
1	33.8	36.2	37.8	80.0	84.0	85.3	167.3	175.4	182.3	509.5	518.3	510.8
51	37.5	40.0	42.8	178.3	181.9	181.8	297.9	303.3	304.9	418.3	426.4	428.5
101	41.8	43.0	42.1	111.3	111.7	109.1	224.1	234.6	241.5	466.4	481.6	491.5
151	24.5	25.5	27.2	88.7	95.3	100.5	223.5	232.4	237.4	387.9	399.0	405.2
201	30.6	34.1	36.5	122.4	126.9	132.0	221.2	228.2	233.2	577.2	598.6	595.3
251	45.4	49.0	51.4	134.1	140.8	145.9	370.9	380.9	385.8	621.9	634.3	640.6
301	39.5	41.8	44.2	118.8	122.3	124.4	251.9	259.5	262.3	461.9	471.4	474.9
351	20.6	22.7	25.1	74.1	79.7	83.5	242.8	253.1	258.0	665.1	683.3	675.4
401	23.9	26.9	29.8	125.7	132.8	137.1	283.7	291.8	298.7	771.8	793.4	801.8
451	35.2	37.8	39.0	127.1	132.2	136.5	202.3	210.1	214.0	474.7	486.9	490.7
Long Term		49.0			181.9			380.9			699.5	

storage. For each operation rule and each case, target demands were varied to make full use of usable storage without obtaining undeclared shortages.

For the operation rule providing surpluses, final target demands did not change appreciably from the constant target demands, but the average annual use increased appreciably, because declared surpluses exceeded declared shortages. Increased yield ranged from 10 percent for the 30% demand level down to 5 percent for the 85% demand level.

For the operation rule not declaring surpluses, target demands rose appreciably, and average annual yields did also. Average delivery, accounting for shortages but no overages, rose from 3 to 4 percent.

Considering that a small percentage increase in firm yield at little expense can amount to a significant economic gain, employment of a flexible operation rule can provide significant but not outstanding gains.

CONCLUSIONS

In general, it can be concluded that, even where long records of streamflow are available, estimated yields obtainable through regulation are highly undependable. First of all, Figure 3 illustrates that severe droughts can occur that could hardly be anticipated through study of variations within long periods (40 or more years, in this illustration). Secondly, even if streamflow sequences conform to a simple statistical model, such as the first-order Markov process, estimates of storage required to produce a firm yield without shortages in a 50-year period differ by as much as a factor of 2.0 in 10 cases selected at random. Unreliability expressed in these terms (percentage error in storage requirement) appears to be relatively independent of the type of runoff or target yield.

The severity of a drought is a function of the operation or physical process that is affected by that drought. Table 2 illustrates that the most severe short-duration droughts are not ordinarily the most severe long-duration droughts. Thus, where little or no storage regulation is provided, short-duration droughts can impact heavily on an irrigation operation whereas long-duration droughts (which are not so severe in the short term) would not be as detrimental. On the other hand, where a high degree of storage development exists, short-duration droughts are relatively unimportant. It can be inferred from this that, if the record used as a basis of design happens to contain only a moderate short-duration drought but an unusually severe long-duration drought, economics would dictate a low degree of development. In the reverse case, a high degree of development would be favored. If the favored design actually is adopted, there is more than a normal chance that it will be inadequate, simply because the "design drought" tended to be less severe than would normally be expected in the observation period. This bias might largely be avoided by use of stochastic analysis of the historical data.

Many theoretical studies of potential yield are based on providing a uniform yield, whereas virtually all water uses vary seasonally. Figures 1 and 2 illustrate the effects of these seasonal use variations on storage requirements. Even though the seasonal variations in use are moderate (not greater than 30 percent from the average), the effects on storage requirements can be extreme. However, in some streams they are minor, and there appears to be no simple procedure for assessing this effect. It appears that a detailed sequential analysis of the runoff-storage-use process is necessary in order to make a reliable estimate of required storage.

Lastly, a policy of providing a fixed service independently of water availability appears to be somewhat inefficient. If contract or other provisions can be made to reduce water use in times of shortage on a prearranged basis (such as by increased price) and possibly to increase the effective use of water in times of surplus (such as by reduced prices), then the overall dependable yield of a given storage facility can be increased by a small but significant percentage.

ACKNOWLEDGMENT

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REFERENCES

1. Close, E.R., Beard, L.R., Dawdy, D.R., "Objective Determination of Safety Factor in Reservoir Design," Jour Hydr Div, ASCE. Vol. 96, No. HY5, May 1970.

2. Fredrich, A.J., "Techniques for Evaluating Long-Term Reservoir Yields," presented at ASCE National Meeting on Water Resources Engineering, New Orleans, 8 February 1969.

3. Moss, M.E. and Dawdy, D.R., "Application of Sensitivity Analysis to Reservoir Design and Worth of Streamflow Data," presented at Symposium on Statistical Hydrology, University of Arizona, Tuscon, Arizona, 1971.

4. U.S. Army Corps of Engineers, The Hydrologic Engineering Center, "Reservoir Yield," Computer Program 23-J2-L245, Sacramento, California, 1966(a).

5. U.S. Army Corps of Engineers, The Hydrologic Engineering Center, "Monthly Streamflow Synthesis," Computer Program 24-J2-L243, Sacramento, California, 1966(b).

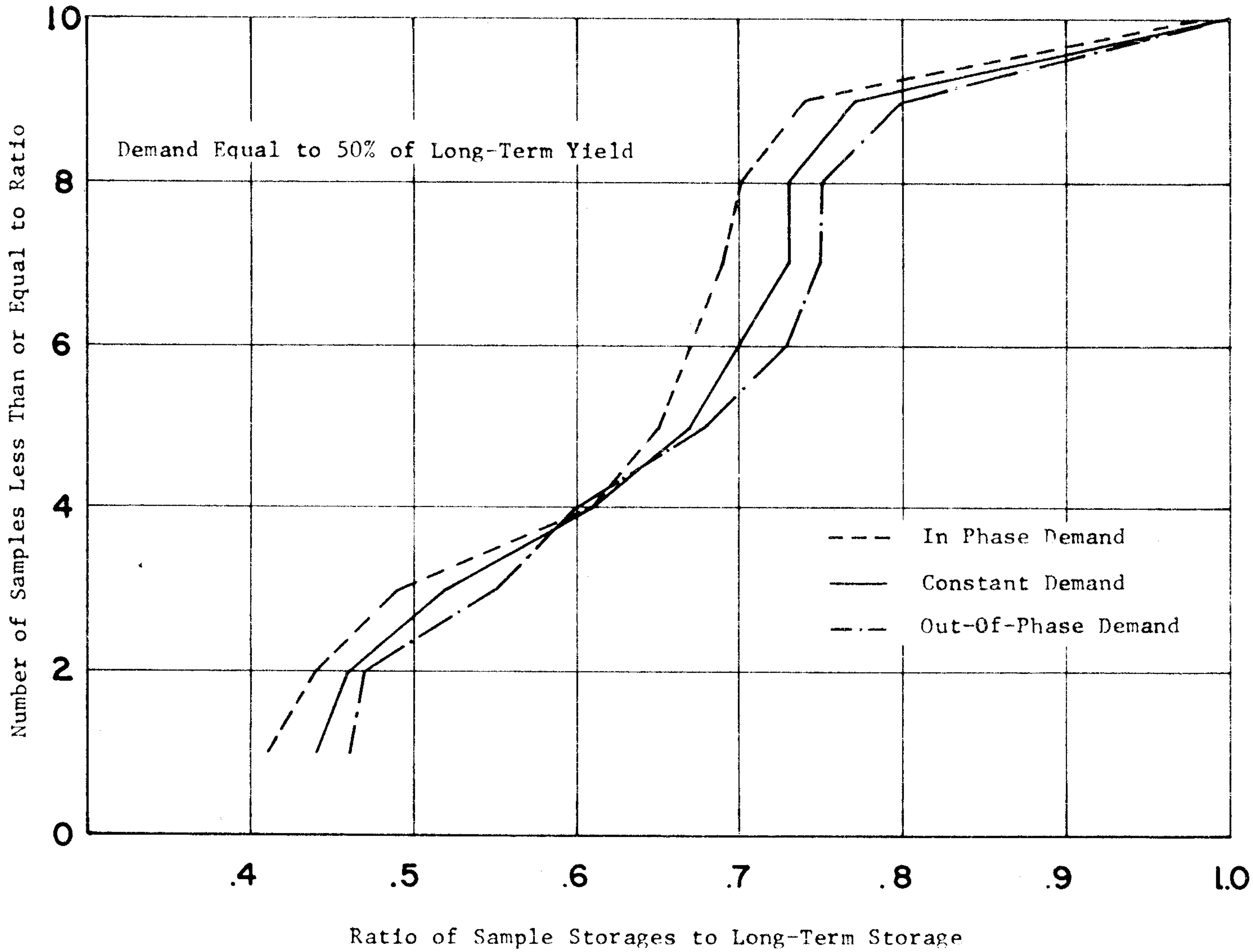

Figure 1. SAMPLE STORAGE REQUIREMENTS, ARROYO SECO

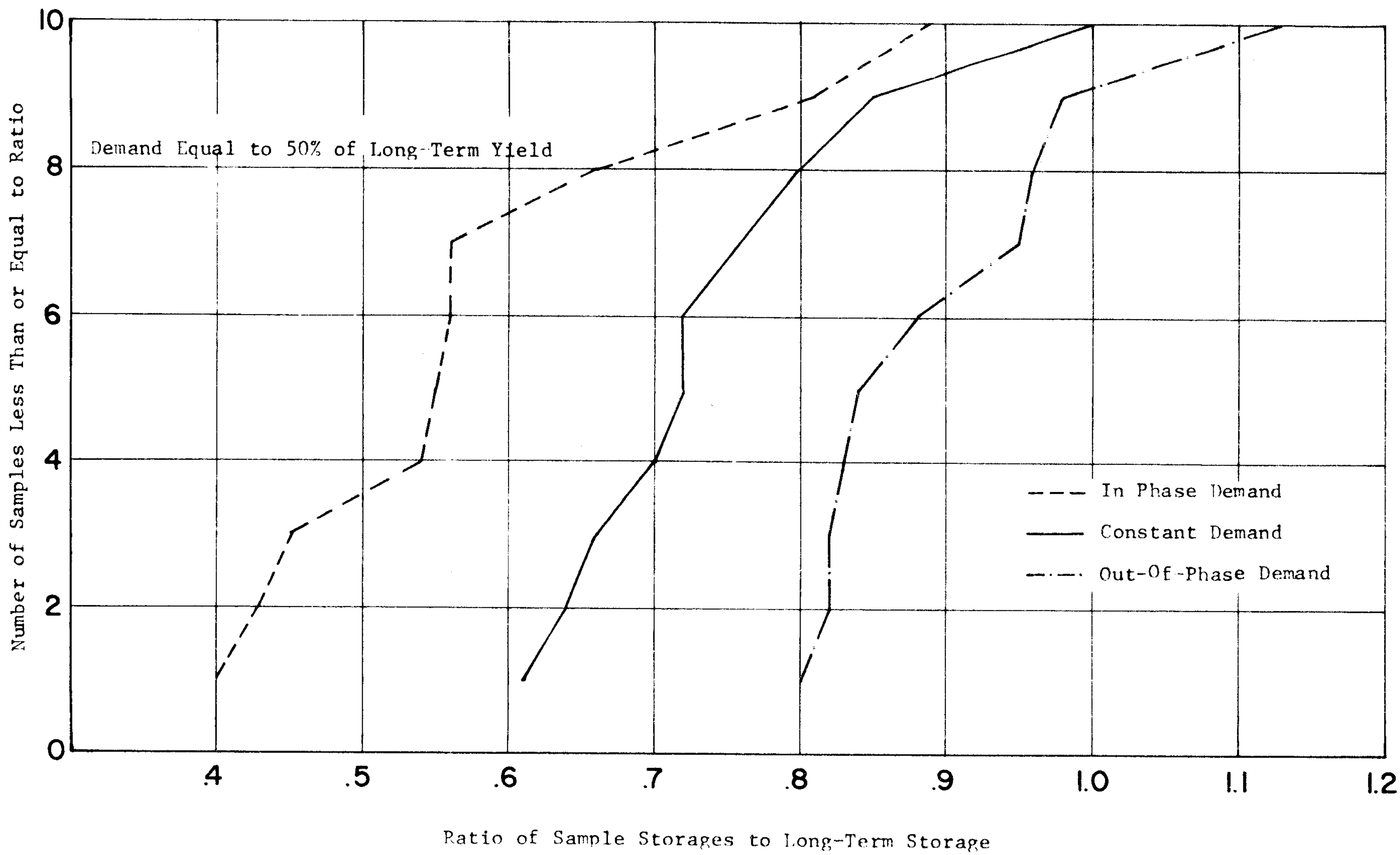

Figure 2. SAMPLE STORAGE REQUIREMENTS, WILLAMETTE RIVER

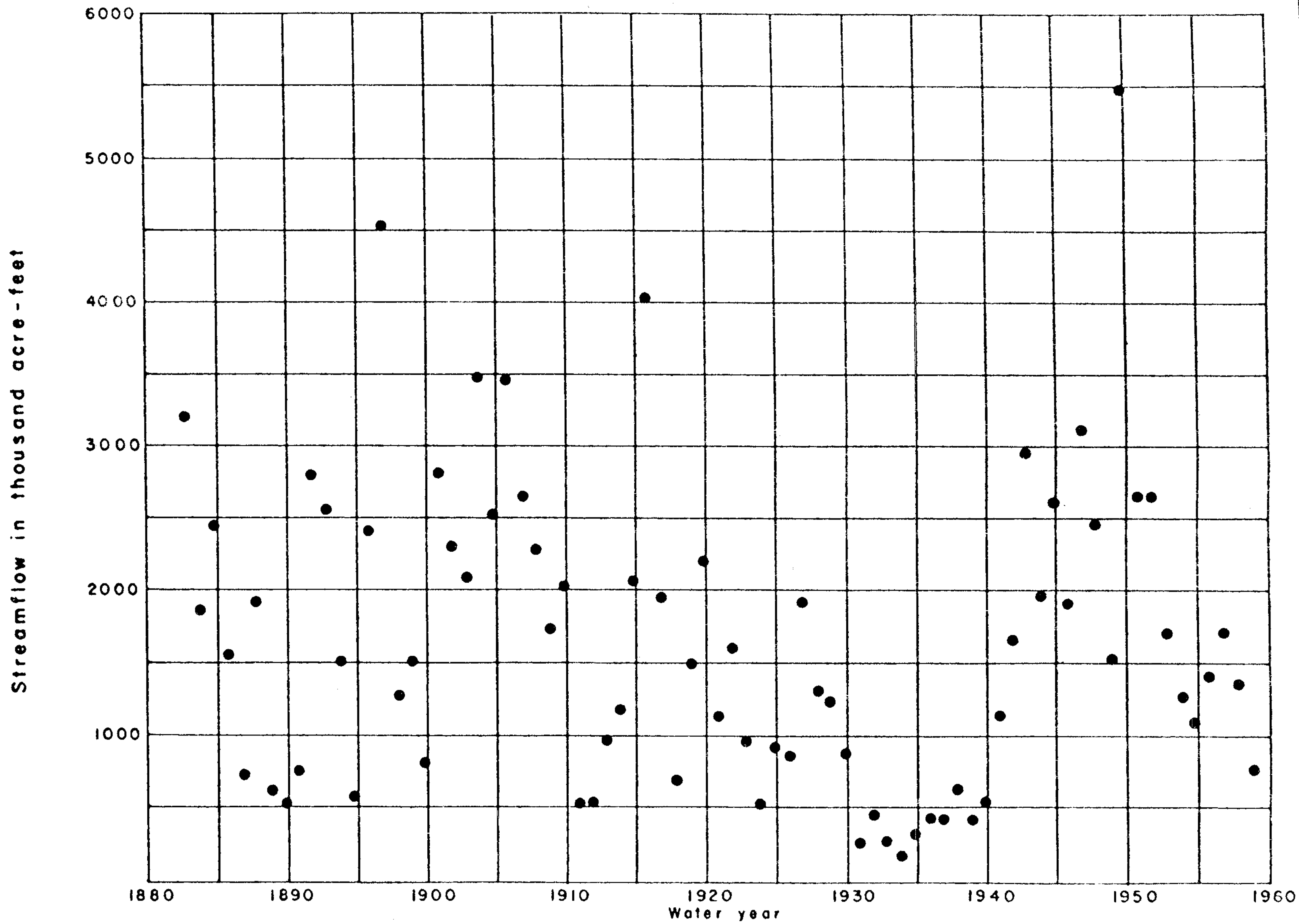

Figure 3. ANNUAL-STREAMFLOW SEQUENCE
Red River of the North
at Grand Forks, North Dakota

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