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Storage capacities required to maintain specific yield were determined independently for each half of twelve long streamflow records on unregulated streams in two-thirds of the cases, design varied by a factor of two, indicating the inadequacy of design based upon the repetition of past streamflows. A method was described for generating monthly streamflows that have the basic frequency and persistence characteristics of the recorded data. It was concluded that the simulated streamflows had the advantage that any length of record could be generated and that the expected benefits and statistical consequences of particular capacities could be determined.

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HYDROLOGIC SIMULATION IN WATER-YIELD ANALYSIS

By Leo R. Beard[1]

INTRODUCTION

As a result of the worldwide "population explosion," in many regions it is becoming increasingly necessary to develop water resources to the maximum practical degree. It will therefore be necessary to store water on the surface and underground for longer periods of time and to save water from wet cycles for use during droughts. Because of the general increase in the value of water, such long-period storage is becoming increasingly economical.

When a water resource project is planned, there is no way of knowing the exact sequence of hydrologic events for which the project must be designed. Consideration should be given to all sorts of sequences or "series" of hydrologic events that can occur and to the likelihood that certain adverse categories will occur.

For example, the examination of a streamflow record might show that a particular dependable yield would have been obtained if a calculated amount of water could have been released from storage during a critical 4-yr period in the past. Knowing that the future will certainly differ from the past in some respects, it is necessary to consider the possibility

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and likelihood that a more or less severe 4-yr drought will occur, or that a shorter or longer drought will occur.

It would be most desirable for this purpose to have a record of streamflow that is thousands of years long and that represents conditions as they will be during the project life. Such a long record could be divided into parts of desired length, and various alternative plans could be compared on the basis of many possible hydrologic sequences instead of on the basis of one record that is usually too short. Because such a long record is never available, it would be highly desirable to construct or "simulate" sequences or "series" of streamflows that could as likely occur at the location as any other sequence and would, in fact, be as good as an actual record. While such a goal may never be achieved, it can well be approached by appropriate hydrologic analyses.

SIMULATION PROCEDURE

The increasing complexity of water resource planning problems makes simplified mathematical procedures such as the Rippl diagram and queueing theory of decreasing utility. It is becoming more and more necessary to make a detailed month-by-month or day-by-day examination of the operation scheme for any water resources project or system in relation to recorded or hypothetical streamflows. Accordingly, the most promising approach to a comprehensive streamflow analysis for planning, design, and operation purposes appears to be in the construction of simulation models for generating realistic values of streamflow. This concerns "stochastic hydrology," which is named after the mathematical process governing the variation of any phenomenon in relation to time, referred to as a "stochastic" process.

One logical way of obtaining hypothetical series of streamflows might be to rearrange observed flows in different sequences. This would keep all individual monthly magnitudes within reasonable range and would certainly be useful in many design problems if the rearrangement is legitimate. However, in almost all streams, there is a tendency for wet months to be followed by above-normal monthly streamflows and for dry months to be followed by below-normal streamflows. This "persistence" tendency is measured mathematically by the serial correlation coefficient of successive monthly streamflows. Also, it is reasonable to infer from recorded magnitudes and general experience that magnitudes intermediate between recorded values, and beyond the range of recorded values, can occur.

Accordingly, it is considered best to generate streamflows from continuous frequency curves of flows for each calendar month, which are based on the record, while assuring a serial correlation similar to that observed in the record. This is done in effect by multiplying the antecedent streamflow by a positive coefficient derived from the record and adding a random component. The first (correlated) component assures a tendency of persistence equal to that observed in the record, and the random component (which can be above or below normal with equal likelihood) provides the portion of variance in the new month that is not related to the antecedent month. This random component would be associated with unpredictable weather changes and other variations in the new month that are not related to antecedent conditions. This procedure has been used in previous Corps of Engineers studies and has been described by H. A. Thomas.

In the simulation procedure developed by The Hydrologic Engineering Center, streamflows are generated for each calendar month from a log Pearson Type III curve that best fits the observed data for that month, and in such a manner as to preserve the degree of correlation observed between flows of that calendar month, flows for the preceding calendar month, and the average flows of the six months antecedent to the preceding month. The detailed procedure and tests of its adequacy are described in a previous paper. In essence, the generated streamflows will have the same frequency and persistence characteristics as do the recorded streamflows.

A simulation equation of the following form is established for each calendar month; that is,

$$X_n = RX_1 + X_r(1 - R^2)^{\frac{1}{2}} \tag{1}$$

in which X_n = log of flow for the current month, expressed as normal standard deviate; X_1 = log of flow for the antecedent month, expressed as normal standard deviate; X_r = random normal standard deviate; and R = serial correlation coefficient.

In order to simulate monthly streamflows for a given location, a set of three frequency statistics (mean, standard deviation, and skew coefficient of flow logarithms) and the correlation coefficient must be computed for each month from observed data. Thus, 48 statistics are required for the 12 months.

In generating simulated streamflows, normal standard deviates (X_n-values) are first generated by the use of Eq. 1, and then transformed to conform with the log Pearson Type III function having the proper mean, standard deviation, and skew coefficient for the calendar month concerned. This process is repeated month by month. This generation sequence preserves frequency characteristics accurately, which is not ordinarily true if the normal standard deviate step is omitted.

SPLIT-RECORD TEST PROCEDURE

The history of statistical applications is replete with cases of testing the validity of procedures using (directly or indirectly) the same data on which the procedure was based. This may test the arithmetic, but not the model. It is essential that any procedure or mathematical model derived statistically be tested by use of data independent of the values used in its derivation. This can be done by using half of a record to calibrate the model and the other half for testing. The two halves can then be interchanged, and a second calibration and test made.

A split-record test can be illustrated as follows:

1. The minimum 54-month runoff observed in one half of a record is considered to constitute an estimate (as a forecast) of the minimum 54-month runoff in the other half.

2. The minimum 54-month runoff is a simulated streamflow series of half-record length, derived from data in the first half of the record, is considered to be an alternative estimate of the second-half quantity.

3. It can be reasoned that the estimate that is more nearly adequate as tested by the other half of the record is indicated to be the better estimate. However, because the second (test) half of the record might be abnormal, one such test is not conclusive.

4. Nevertheless, it can be stated that the procedure that yields estimates closer to the test value in the majority of a large number of cases is the more dependable of two procedures.

The split-record test is highly insensitive because of chance variations in the test half of the record (considered above). A perfect estimating procedure would score improvements in only about two-thirds of the test cases. Consequently, a great number of tests is required to produce significant verification.

TEST OF MINIMUM-RUNOFF ESTIMATES

Table 1 shows the results of a test of minimum 54-month (4-1/2 yr) runoff estimates based on simulated streamflows, as compared with similar estimates based directly on recorded streamflows. Using statistics for each half of the streamflow record at seven stations in the United States,

TABLE 1

Minimum 54-Month Runoff Comparison - Observed and Generated Series

Station		323		501		514		534		808		1107		1123	
Half Record		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Years		22	22	38	38	29	29	22	22	21	21	28	28	25	25
Units		inches		1,000 acre-feet		inches		inches		1,000 acre-feet		1,000 acre-feet		1,000 acre-feet	
Generated Series	1	45.0	15.1	4220	2750[a]	27.4	21.9[a]	43.9	18.2	4210	2610[a]	271[a]	236[a]	40.0	84.4
	2	21.2[a]	27.3[a]	3790	2950[a]	27.4	20.8[a]	28.4[a]	30.8[a]	3720	3420[a]	226[a]	278[a]	46.5	80.8
	3	23.2[a]	15.8	3680	2040[a]	30.9	28.8[a]	24.4[a]	28.4[a]	3320[a]	990	352	219[a]	33.2	65.2[a]
	4	23.1[a]	39.8[a]	5000	2660[a]	29.4	24.2[a]	49.8	39.7[a]	4740	1750[a]	238[a]	177[a]	75.9	74.4[a]
	5	19.3[a]	33.1[a]	4850	3990[a]	31.3	18.1	35.1[a]	23.6	3980	1440[a]	225[a]	166[a]	95.0	60.9
	6	23.1[a]	29.1[a]	2110[a]	3100[a]	27.4	22.9[a]	29.8[a]	17.8	2780[a]	3610[a]	237[a]	289[a]	57.3[a]	79.1[a]
	7	47.8	18.8[a]	4810	3360[a]	28.9	24.2[a]	42.3	19.7	4040	2360[a]	236[a]	257[a]	47.7	77.8[a]
	8	38.2	16.5	4340	2080[a]	29.3	22.0[a]	63.2	28.3[a]	4230	890	239[a]	238[a]	86.7	75.2[a]
	9	24.5[a]	35.5[a]	4100	3240[a]	30.1	25.3[a]	32.1[a]	48.3[a]	2600[a]	850	364	234[a]	35.0	53.6
	10	34.0	26.4[a]	3330[a]	2660[a]	26.2	25.0[a]	27.0[a]	27.4[a]	2870[a]	3100[a]	275[a]	225[a]	48.2	47.3
Median		23.8[a]	26.9[a]	4160	2850[a]	29.1	24.2[a]	33.6[a]	27.8[a]	3850	2050[a]	238[a]	236[a]	47.9	74.7[a]
Observed		30.6	17.2	3570	1190	23.7	18.2	39.2	26.1	3590	1420	280	161	74.6	64.5

[a] Synthetic-flow value that is a better estimate of observed flow in the opposite half of record than the corresponding observed flow.

ten series of simulated streamflows were generated (140 series in all). The minimum 54-month runoff was determined for each recorded and simulated streamflow series. These are summarized in Table 1. Where a quantity based on simulated streamflows agrees better than does its corresponding half-record value with the value observed in the opposite half of the record, it is marked with a superscript.[a]

In 58% of the cases, the estimate from the single simulated series is closer than that from the actual record. This must be accidentally high, because generated series cannot yield a more dependable estimate than the actual record of the same length. Thus, the number of cases in which a single simulated series gives a superior estimate should not exceed 50% of all cases. The important consideration is that the result appears to justify considerable confidence in the use of the model.

If there is much advantage to be gained from the use of runoff simulation procedures, it would be because of the ability to provide longer series of runoff or more series of runoff than available in the record. Table 1 illustrates that there is some gain in accuracy when there is a number of series generated and the median estimate is selected. In this case, ten of the fourteen median generated values (71%) are closer estimates than the corresponding record values, compared to 58% for individual series.

TEST OF STORAGE DETERMINATIONS

A feasible procedure for testing the use of a streamflow simulation model in making yield or storage estimates must be greatly simplified in comparison with the extremely complex conditions that prevail in an actual hydrologic design problem. The test made herein is based on the capacity determinations for producing a yield of specified seasonal distribution equal on an annual basis to about 95% of the geometric mean annual runoff for the stream. This is a fairly high degree of regulation and would entail a carryover of water for many years on most streams.

In solving for storage requirement, it is first necessary to define the conditions acceptable for a firm supply of water. A requirement that no shortage will occur is not reasonable, because this would make the required storage a function of the length of streamflow series used, as longer periods tend to encompass more severe droughts. In this study, the shortage index described by the writer at the 13th General Assembly of IUGG was used. This shortage index is obtained by computing annual shortages as a ratio to the firm yield and summing the squares of these shortages over a period of 100 yr. A shortage index of 0.25 (used in this study) would thus permit a single shortage of 50% in 100 yr, or 25 shortages of 10% each in 100 yr, or any combination of shortages whose squares would total 0.25 in 100 yr.

For the purpose of this test, it was also necessary to specify an initial storage condition for each period. In actual design, the initial storage might be zero, because each reservoir, when constructed, would be empty. However, demand for service from a reservoir usually grows gradually after construction, and the first few years ordinarily are not critical. It was, therefore, considered that the test herein would be more representative of actual design needs if a typical initial storage were used. Accordingly, all routings were made on the basis that the reservoir is half full at the beginning of the routing period.

Using the procedures described above, storage determinations were made for twelve stream gaging stations in the United States having long records and negligible regulation. These are summarized in Table 2 and illustrated in Fig. 1.

One of the striking results of this comparison is that space requirements derived from the two halves of the same record differed by a factor of two or more in two-thirds of the cases. It will be noted that these determinations were based on half-record lengths in the order of 25 yr. Accordingly, storage determinations for producing relatively high yields can be easily in error by a factor of two or more when based directly on 25 yr of record.

An examination of Table 2 shows that, of the 24 sets of storage determinations, only nine estimates (38%) based on single simulated series were closer to the storage requirements of the opposite half of the record than were the corresponding estimates based directly on the record. When estimates are taken as a median of five determinations from simulated series, all based on the same record half, twelve of the twenty-four shown (50%) indicated improvement over those based on the record. While this set of comparisons is not large enough to be conclusive, the results indicate that determinations based on a single

TABLE 2

Estimates of Storage Requirements

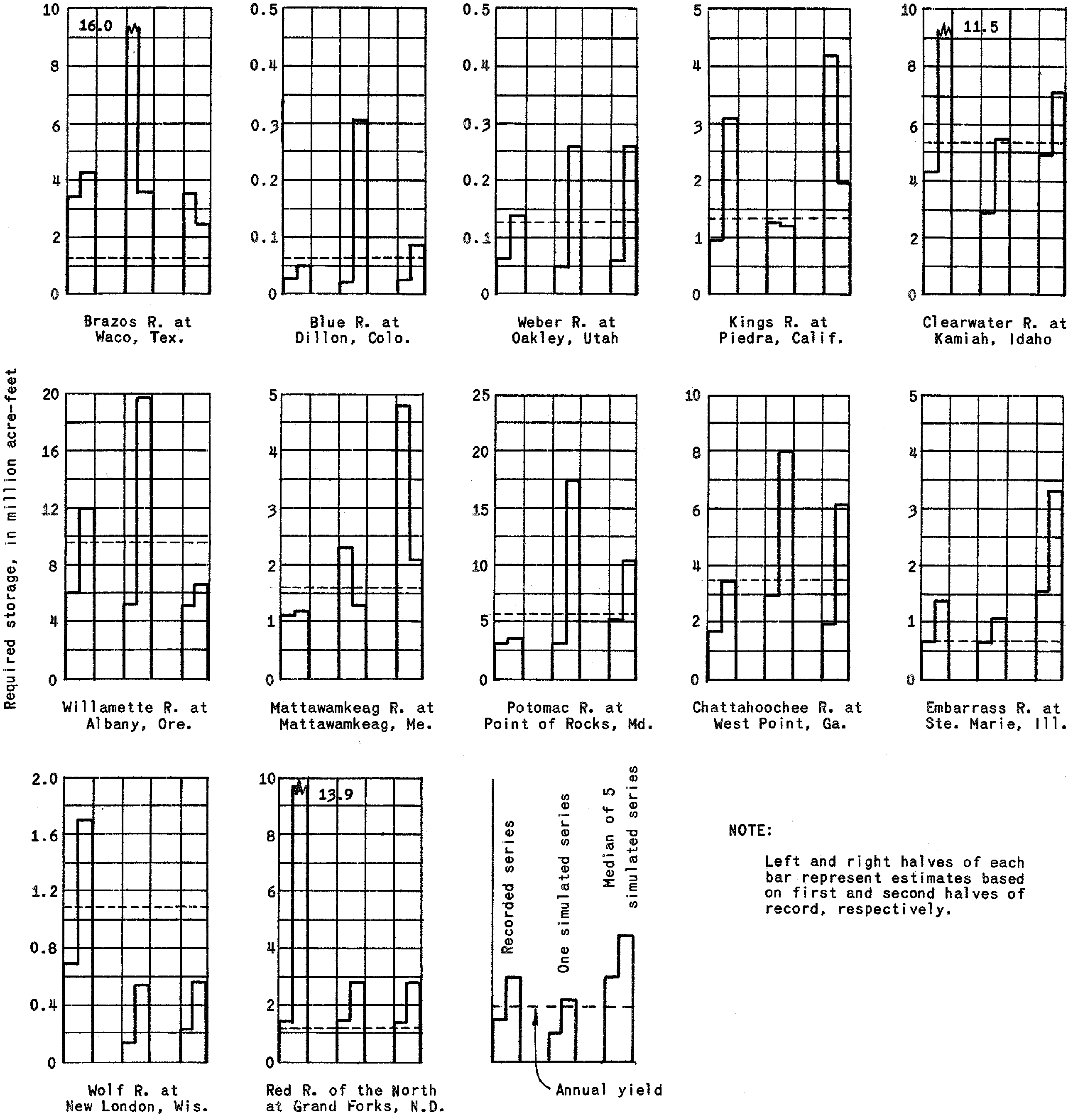
Stream	Annual yield, in acre-feet	Acre-feet of storage required, assuming reservoirs half full at start					
		Based on First Half of Record			Based on Second Half of Record		
			Simulated			Simulated	
		As recorded	Single series	Median of five	As recorded	Single Series	Median of five
Mattawamkeag	1,620,000	1,180,000	2,660,000	4,770,000	1,210,000	1,210,000	2,100,000
Potomac	5,870,000	3,090,000	2,960,000	5,000,000	3,830,000	17,400,000	10,900,000
Chattahoochee	3,420,000	1,730,000	2,840,000^{a}	1,870,000^{a}	3,490,000	8,000,000	6,120,000
Embarrass	671,000	699,000	600,000	1,530,000^{a}	1,380,000	1,020,000^{a}	3,290,000
Wolf	1,080,000	706,000	137,000	194,000	1,720,000	559,000^{a}	559,000^{a}
Red	1,090,000	1,250,000	1,310,000^{a}	1,310,000^{a}	13,900,000	2,710,000^{a}	2,710,000^{a}
Brazos	1,320,000	3,350,000	16,000,000	3,570,000^{a}	4,320,000	3,540,000^{a}	2,490,000^{a}
Blue	70,000	30,200	23,600	27,300	50,900	318,000	90,800
Weber	131,000	66,200	52,500	63,500	141,000	273,000	273,000
Kings	1,340,000	1,000,000	1,300,000^{a}	4,220,000^{a}	3,120,000	1,260,000^{a}	1,950,000^{a}
Clearwater	5,380,000	4,360,000	2,940,000	4,920,000^{a}	11,500,000	5,550,000^{a}	7,140,000^{a}
Willamette	9,500,000	6,000,000	5,200,000	5,200,000	11,900,000	19,800,000	6,800,000^{a}

[a] Estimate closer to observed value in opposite half of record.

series equal in length to the record series are somewhat inferior to those based on the record, as would be expected. Median estimates based on five simulated series are superior to those based on a single-simulated series, and about as good as those based directly on the record. The logical inference is that medians based on more numerous series would show considerable improvement, as illustrated on Table 1.

Inspection of Fig. 1 reveals that, in some cases, there is a relatively high storage requirement indicated by both of the simulation estimates in comparison with both of the record estimates, and in other cases the reverse is true. It is exactly in this circumstance, where recorded flows might be seriously nonrepresentative, that the application of simulation procedures is potentially of greatest benefit. Such benefit would be assured, however, only when the simulation model has been thoroughly tested and when sufficient experience in its use has been gained to instill confidence.

While the median determination for a number of simulated series might be considered the best estimate, the various determinations based on the individual simulated series will also be of value as an indication of possible outcomes during the actual project operation. Perhaps one unusual sequence will reveal a potential condition that could not be tolerated in actual project operation. Also, the determination based on actual recorded values must be given special consideration, inasmuch as there is always a possibility of exceptional circumstances that do not fit the simulation model, although the model may have been tested extensively.



Brazos R. at Waco, Tex.

Blue R. at Dillon, Colo.

Weber R. at Oakley, Utah

Kings R. at Piedra, Calif.

Clearwater R. at Kamiah, Idaho

Willamette R. at Albany, Ore.

Mattawamkeag R. at Mattawamkeag, Me.

Potomac R. at Point of Rocks, Md.

Chattahoochee R. at West Point, Ga.

Embarrass R. at Ste. Marie, Ill.

Wolf R. at New London, Wis.

Red R. of the North at Grand Forks, N.D.

NOTE:

Left and right halves of each bar represent estimates based on first and second halves of record, respectively.

FIG. 1. COMPARISON OF STORAGE DETERMINATIONS

SIMULATION USE IN PROJECT PLANNING

Present practice in the design of water resource projects includes the computation of project benefits on the assumption that a unique series of runoff (usually a repetition of the record) will occur and that specified demand projections, interest rates, and price levels will prevail. It would be highly unlikely that the selected combination of these factors will adequately represent the best estimate of expected project benefits, particularly in view of the complexity of interrelated effects among the variables.

To obtain a stable or reliable estimate of project accomplishments, it is necessary to examine the various ways in which all of the pertinent factors can occur with various probabilities, and to give some consideration to all possible eventualities. In a complex problem such as this, a practical approach to solution is to use the "monte-carlo" technique of selecting random values of each independent variable in numbers proportional to their probability of occurrence. Then a benefits computation can be made for each combination of variables. An average of these benefits represents an unbiased estimate of "expected benefits."

Variables that are probably the most influential in an "expected benefits" study of a water resource project are runoff and population projections, although a projection of price levels in relation to interest rates can be extremely important. Random runoff projections can be made by use of a streamflow simulation procedure as described herein. Of course, the necessity to perform 10 or 20 benefits evaluations makes the use of an electronic computer essential.

SIMULATION USE IN PROJECT OPERATIONS

In operating water resource projects, decisions must often be made that will affect project accomplishments over many future months, without knowledge of runoff that will occur. These decisions must be based on probability considerations and are usually a "judgment" type of decision based on studies of historical sequences and on some rough probability projects, such as upper or lower quartile values of future runoff.

Streamflow simulation will provide an excellent means of making optimum decisions, by virtue of the fact that a number of equally likely future sequences that can reasonably follow observed present conditions can be examined, and an operation that would maximize expected benefits could be selected. As in applications for project planning, the use of an electronic computer would be essential.

FUTURE NEEDS

1. Although little has been accomplished to date (as of 1967) in the actual application of simulated streamflows in water resource design, it is apparent that improvement in present design procedures is vitally needed and that simulation techniques provide a promising approach to such improvement. The simulation model described herein is only one of many possible mathematical models. There is much room for improvement in the model, and continued study for possible improvements is warranted.

2. Simulation models such as described herein require the derivation and use of a large set of statistical quantities from recorded streamflows at the location. It will be desirable to generalize such sets of statistics

in order that they can be coordinated among various rivers and in order that a set can be developed for a location where no record exists.

3. Most water resource projects involve the use of streamflows that occur simultaneously at more than one location. A program similar to the one used herein is described in a previous paper.

4. Dependable use of simulated streamflows in water resource design and operation will require a more comprehensive series of tests and demonstrations than those described herein. These should be accompanied by actual trial applications, so that a realistic assessment of utility can be made.

5. A comprehensive multi-purpose analysis of the water resource project requires the consideration of short-period flows, in addition to the monthly streamflows examined herein. Thus a simulation procedure must be extended to include a provision for generating a realistic series of daily and shorter-period streamflows.

SUMMARY

1. The procedures presently used for basing estimates of storage requirements (for a specified yield) on a study of streamflow data as recorded produce highly questionable results.

2. The problem of determining storage requirements in the ordinary multi-purpose water resource project is far too complex for simple application of mathematical procedures such as the Rippl diagram or queueing theory. It is necessary to examine the operation of a proposed project or system of projects by assuming the repetition of recorded

streamflows or the occurrence of simulated streamflows having the statistical characteristics of recorded flows.

3. A model for simulating streamflows similar to the one used for illustration herein can be used to generate streamflows for any number of series of desired length. Each of these series of streamflows can as reasonably occur during the life of a proposed project as can a repetition of the recorded flows.

4. Advantages to be gained by generating simulated streamflows are as follows:

a. Series of streamflows of length desired for economic study purposes can be generated.

b. This procedure can be repeated any number of times for the purpose of examining a variety of conditions that can occur during project operation. (It is also important to examine the project operation on the basis of the actual recorded streamflows, to make sure that the results obtained are reasonably consistent with those derived from the simulated series).

c. By considering the estimates of project accomplishments based on a variety of simulated streamflow series, a single average or weighted average of the results can be obtained that should be a more dependable estimate of expected project accomplishments than can be obtained from any single series of streamflows.

5. It must be recognized that, even if it were possible to make a perfect determination of yield and storage requirements on the basis of

expected runoff variations, actual events that occur during project operation can be seriously abnormal. Thus, even though an optimum design is adopted, it is entirely possible that the particular series of streamflows that occur during operation would either not fully utilize the project facilities or would overtax them. The use of simulation procedures cannot entirely remove the chance element in the design and construction of water resource projects.

CONCLUSIONS

Hydrologic simulation has some important immediate applications, and yet there is much need for its development. Most important, if its potential application and limitations are fully understood, it holds great promise for improving determinations of expected project yield and for making operation decisions that will bear more and more heavily on the social and economic welfare of large segments of the world's population.

ACKNOWLEDGMENTS

The computer program for simulating monthly streamflows used herein was developed in The Hydrologic Engineering Center of the Corps of Engineers, and the tests described herein were performed in the Center. The program was written and many mathematical and hydrologic parts of the study were developed by H. A. Keith, Hydraulic Engineer at The Hydrologic Engineering Center.

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