US Army Corps
of Engineers
Hydrologic Engineering Center

Simulation of Daily Streamflow

April 1968

TP-6

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
April 1968	Technical Paper	

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Simulation of Daily Streamflow	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Leo R. Beard	**5e. TASK NUMBER**
	5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616-4687	TP-6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/ MONITOR'S ACRONYM(S)**
	11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Presented at the International Hydrology Symposium, 6-8 September 1967, Colorado State University, Fort Collins.

14. ABSTRACT

The stochastic process of daily streamflow generation is represented by a mathematical model including more than one element of serial correlation and a random component in the generation of a daily streamflow. Differences in statistical and correlation characteristics between high flows and low flows are evaluated and tested. A generalized equation for generating daily streamflow at a single location is suggested.

15. SUBJECT TERMS

synthetic hydrology, statistical models, stochastic processes, streamflow forecasting, Markov processes, statistical methods, correlation analysis, regression analysis, simulation analysis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
U	U	U	UU	22	**19b. TELEPHONE NUMBER**

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

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SIMULATION OF DAILY STREAMFLOW

by

Leo R. Beard[1]

INTRODUCTION

Considerable work has been done by individuals and organizations in developing procedures for simulating annual streamflows and monthly streamflows for the purpose of increasing the reliability of reservoir yield estimates. Some of this work is described in references 1, 2, and 4. It has been observed that relatively minor changes in the sequence of recorded droughts can have major influence on yield obtainable and storage space required at a reservoir project. The purpose of simulating streamflows is generally to produce long series of values that could as likely occur in the future as could repetition of historical values, thus providing a more complete sampling of potential runoff than is represented in flows as they occurred historically. The mathematical model generally used for simulating these streamflows consists of a Markov chain, usually of the first order.

Although fluctuations of flows within a month usually have minor influence on reservoir storage required for conservation purposes, such fluctuations are ordinarily crucial in the determination of reservoir space requirements for flood control. Because of this, and since there are many uncertainties in present procedures and criteria for the design of reservoirs for flood control, simulation of daily streamflows could constitute a major contribution toward improving flood-control

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design. This possibility results primarily from the fact that virtually all available streamflow data at a station would be used in calibrating a simulation model for that location, in contrast with the rather limited use of recorded data in present flood-control design procedures. It is considered that the process would be useful primarily for generating daily flows during flood months, rather than during average or dry months.

The model described herein was based on adequate representation of daily streamflow variations at 7 selected stations listed in table 1.

Table 1

Stations Used in Study

No.	Location
1	Blue R at Dillon, Colorado
2	Apple R nr Somerset, Wisconsin
3	Kern R nr Bakersfield, California
4	Tule R at Porterville, California
5	Kaweah R nr Three Rivers, California
6	Kings R at Piedra, California
7	M. B. Westfield R nr Goss Heights, Mass.

Data used for tests of the model were also limited to these 7 stations, and other data will eventually be used for further testing and possible refinement of the model. It will be noted that some of the results of this study are similar to results of concurrent work reported in reference 3.

BASIC GENERATION MODEL

Inasmuch as most water resources studies must be based on many years of recorded or generated flows (preferably 50 to 1,000 or more), it will usually not be feasible to generate and use daily flows for the entire period of study. Accordingly, the procedure described herein has been based on generation of monthly streamflows and subsequent allocation of the monthly total amounts to each day. Thus, daily flows would only be generated for those months when flow fluctuations within a month are important. The monthly streamflow generator used is that developed in the Hydrologic Engineering Center of the Corps of Engineers and described in reference 1, with the exception that the antecedent 6-month variable is no longer used in the model. For a single station, it consists of a simple Markov chain, with each flow consisting of a random component and a component correlated with the preceding month's flow. Other model characteristics are similar to the ones described herein for daily flow generation.

The mathematical model used for daily streamflow simulation consists of a second order Markov chain, using standardized variates. Daily flows are first classified by calendar month, and their frequency characteristics (logarithmic mean, standard deviation and skew coefficient) for each calendar month are determined from observed data. One statistic would be, for example, the mean logarithm of all flows recorded in January of all years. In order to avoid the logarithm of zero flows, a slight increment equal to .01 times the average monthly flow is added to each daily flow before taking the logarithm. The same amount would subsequently be subtracted from generated flows.

Standardized variates are obtained by subtracting the mean logarithm from the daily-flow logarithm, dividing by the standard deviation, and transforming to normal by use of the following equation, which approximates the Pearson Type III distribution:

$$t = \frac{6}{g}\left[\left(\frac{g}{2}k + 1\right)^{1/3} - 1\right] + \frac{g}{6} \qquad (1)$$

in which t = a normal standard deviate, k = a Pearson Type III standard deviate, and g = the skew coefficient. Standardizing the variates (transforming to zero mean, unit variance and zero skew) is necessary in order to retain the desired degree of skew in the daily-flow logarithms for each calendar month. Combining random and correlated components would change non-zero skew coefficients by an amount that is difficult to determine mathematically.

To determine the order of the Markov chain required for realistic representation of daily flows recorded at the 7 streamflow stations selected for study, correlation studies were made between the standardized variates for each day in three ways: the first correlated with the preceding day only, the second with two preceding days independently, and the third with three preceding days independently. Results for the seven stations are summarized in table 2, which shows that there is a slight average increase in determination when the second antecedent day is considered, but no increase when the third antecedent day is also considered.

Table 2

Required Order of Markov Chain

Station No.	Years of Record	Avg. Determination Coefficients 1st order	2nd order	3rd order
1	46	.9637	.9654	.9656
2	46	.7569	.7860	.7860
3	60	.9581	.9598	.9598
4	50	.9322	.9322	.9322
5	52	.9168	.9169	.9163
6	54	.9162	.9178	.9178
7	52	.8106	.8121	.8121

Table 3 shows that the regression coefficient for the second antecedent day is negative, which would be expected from the fact that an upward trend or downward trend would tend to continue from day to day.

Table 3

Average Coefficients for Twelve Months

Station	Regression coefficient 1st antecedent day	2nd antecedent day	Determination coefficient
1	1.145	-.166	.966
2	.595	.318	.786
3	1.194	-.219	.960
4	.996	-.031	.932
5	1.006	-.050	.917
6	1.089	-.136	.918
7	1.067	-.092	.812

(The coefficient for station 2 is indicated to be positive, but this is believed to be accidental, in view of the low determination for that station.)

TEST OF CORRELATION VARIATION

There is some question as to whether the frequency and serial correlation characteristics of daily streamflows will differ for the same calendar month in wet and dry years. In order to examine the variation of serial correlation for the same calendar month in different years, serial determination coefficients (squares of correlation coefficients) were computed for each calendar month and for each year of record at the seven stations used in this study. For each calendar month, this serial determination coefficient was correlated with the total runoff for the month, using values determined for that calendar month in each year as a separate observation. Results are summarized in table 4, which shows that there is generally some small correlation, but the correlation is not highly significant. Inasmuch as application of different serial determination coefficients would considerably complicate the model from a mathematical standpoint, and in view of the weak indication of variation with monthly streamflow, the serial determination coefficient is assumed to be independent of the amount of runoff during the month.

VARIATION OF STANDARD DEVIATION

The possible variation of standard deviation with monthly runoff for each calendar month among the various years was tested in the same manner as was the serial correlation discussed in the preceding section. Results are shown in table 4. Here the indication is very consistent and statistically significant. The positive regression coefficients indicate that the standard deviation of logarithms in wet months is greater than in dry months (for the same calendar months in different years) which is the reverse of what one might expect. However, the results are considered to be realistic, as well as statistically significant. Accordingly, the standard deviation of flow logarithms within each month in the model is computed as a linear function of the total monthly flow. Such linear functions are computed from recorded streamflows as a different relation for each calendar month.

MONTH-END DISCONTINUITIES

Inasmuch as the monthly streamflows are generated before entering the daily streamflow generator, total monthly amounts are pre-determined insofar as the daily streamflow generator is concerned. Daily flows for each month are first generated by generating correlated standardized variates and transforming these to logarithms by use of the following approximate transform equation for the Pearson Type III distribution:

$$k = \frac{2}{g}\left[\frac{g}{6}\left(t - \frac{g}{6}\right) + 1\right]^3 - \frac{2}{g} \qquad (2)$$

which is simply another form of equation 1. These logarithms are converted to flows, which are added to obtain a monthly total. This sum includes random components and is therefore expected to be somewhat different from the desired total entered from the monthly streamflow model. A ratio of these totals could be applied to each daily streamflow, but this would ordinarily result in discontinuities at the end of each month. In order to avoid this, the random numbers used for that month are preserved in the computer, and new daily values are generated on the basis of a temporary monthly total obtained by multiplying the desired monthly total by the ratio of the desired total to the generated total for the first pass.

Table 4

Relation of Standard Deviation and Serial Correlation to Average Monthly Streamflow

Station	S vs M (1)		$\bar{R}^2$ vs M (2)	
	C (3)	$\bar{R}^2$ (4)	C (3)	$\bar{R}^2$ (4)
1	-.042	.181	-.346	.029
2	.021	.116	.322	.127
3	.026	.144	.022	.001
4	.000	.162	-.105	.074
5	.076	.205	-.043	.043
6	.062	.191	-.041	.016
7	.065	.052	-.076	.020

(1) Average of 12 monthly correlations of standard deviation of daily flow logarithms to logarithm of monthly flow.

(2) Average of 12 monthly correlations of serial determination coefficients of daily-flow logarithms with logarithm of monthly flow.

(3) Linear regression coefficient

(4) Determination coefficient

The flows resulting from the second-pass generation will very nearly total the desired monthly amount. These can therefore be multiplied by a ratio to obtain the exact monthly total without creating a serious discontinuity at the end of each month.

SUMMARY OF PROCEDURE

Generation of daily streamflows for a location where daily flow records exist and where monthly total flows for the periods of generation are given is accomplished by two elaborate computer programs usable in high-speed computers. The analysis program computes for each of twelve calendar months:

a. The mean, serial correlation coefficient, and skew coefficient of the logarithms of all recorded daily flows for that calendar month, and the correlation coefficient between flow logarithms of each day and the second antecedent day.

b. The linear regression coefficients of the standard deviation of daily-flow logarithms within each month of record to the logarithm of total flow for the month.

The synthesis program accepts the total flow for each month, and proceeds as follows:

a. Generates for each day standardized variates conforming to the serial correlation observed in the recorded data for that calendar month, using the following equation:

$$X_{i+2} = b_1 X_{i+1} + b_2 X_i + (1-\bar{R}^2)\, X_r \qquad (3)$$

in which X_i, X_{i-1} and X_{i-2} are standardized variates for successive days, X_r is a random standardized variate, b_1 and b_2 are regression coefficients derived from correlation coefficients obtained by the analysis program, and $\bar{R}^2$ is the determination coefficient for the regression equation.

b. Obtains the logarithm of the monthly mean flow as a first estimate of the mean logarithm of daily flows to be generated.

c. Computes the standard deviation of flow logarithms using the regression equation derived in the analysis program for the calendar month.

d. By means of equation 2, transforms the standardized variates to flows using the above mean and standard deviation and the skew coefficient derived in the analysis program.

e. Adds the difference between the logarithm of the given monthly total flow and the logarithm of the total generated flow for the month to the logarithm of the given monthly total flow and repeats steps a, c and d (second pass).

f. Multiplies each transformed second-pass flow by the ratio of given total monthly flow to total generated monthly flow.

TEST OF OVER-ALL RESULTS

Since the daily streamflow generation model is considered to be needed for generating streamflows during flood periods and of little practical application in generating streamflows during drought periods, over-all tests that have been made to date were restricted to high streamflows. They consist essentially of obtaining the maximum one-day, 3-day and 10-day flows for each year of record and comparing their frequency distributions with corresponding quantities from the generated flows. Results of these comparisons are not complete, but partial results illustrated in table 5 indicate that the generator is producing reasonable results insofar as high flows are concerned.

Table 5

Comparison of Recorded and Generated Maximum Flows
Kern River at Bakersfield, 60 Years

Duration	Event	Recorded	Generated
1-day	Max	15,500	12,200
	Min	890	968
	Median	3,360	2,620
3-day	Max	11,000	11,700
	Min	881	948
	Median	3,250	2,580
10-day	Max	9,180	11,000
	Min	836	930
	Median	2,870	2,370

CONCLUSIONS

It is believed that a daily streamflow generator can contribute considerably to water resources studies that are sensitive to variation of high streamflows. Since most water resources studies must be based on long periods of recorded or generated streamflows, it ordinarily is not practical to generate and use daily streamflows for the entire period of study. Accordingly, a daily streamflow generator that will accept monthly streamflows generated by another model is highly desirable. A reservoir study could then be based on monthly streamflows except for those relatively few months when variations of flow within the month are important.

The daily streamflow generator described herein consists of a 2-pass generation by use of a second-order Markov chain applied to standardized variates derived from a logarithmic Pearson Type III distribution. It is considered to give reasonably good results, as shown herein, but will warrant further testing and possible refinement.

ACKNOWLEDGMENT

The daily streamflow generator described herein was developed in the Hydrologic Engineering Center of the Corps of Engineers. Much of the developmental work and practically all of the computer programming was done by William L. Morse. Denver L. Mills made some of the test studies required for verification of the model.

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