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14. ABSTRACT
In 1982, the National Weather Service (NWS) published criteria for developing the spatial and temporal precipitation An electronic computer procedure was described that extracted a maximum degree of pertinent information from monthly streamflow data and generated values whose statistical characteristics were consistent with those of the observed monthly streamflow. Multiple linear regression of the data transformed to unit normal standard deviates was used. A procedure was described for using data that were not simultaneous at all recorded locations and that would permit formulating an interrelated streamflow generator for ungaged stations.

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USE OF INTERRELATED RECORDS TO SIMULATE STREAMFLOW

by

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SYNOPSIS

Streamflow simulation is usable in water resources design for the purpose of extracting pertinent information from streamflows at recorder locations and using that information to generate additional values for those locations, and values for additional locations, that could as reasonably occur in the future as could repetition of past events. An electronic computer procedure is described herein that extracts a maximum amount of pertinent information from monthly streamflow data and generates values whose statistical characteristics are consistent with those of the observed monthly streamflows. Multiple linear regression of the data transformed to unit normal standard deviates is used. The transform is accomplished by fitting each month's data (incremented slightly) to a logarithmic Pearson Type III curve. A procedure is described for using data that are not simultaneous at all recorder locations and that would permit formulating an interrelated-streamflow generator for ungaged locations.

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INTRODUCTION

The writer has demonstrated[2] that classical methods of evaluating storage requirements (based on the recorded sequence of streamflows) are deficient, and that improved estimates can be made by use of streamflow simulation procedures. The simulation model for a single location given in the paper cited as reference 2 is expanded herein for use in simulation of streamflows at any number of stations where streamflows are interrelated.

The presentation herein will be limited to a description of the streamflow simulator model and its accuracy in duplicating streamflow characteristics. The need for and potential uses of streamflow simulation were discussed in reference 2.

THE MODEL

In order to minimize the random (unrelated) component of each month's streamflow in a simulation model, multiple regression technique is employed. An entirely separate regression equation is used to generate streamflows for each different calendar month at each different station, using the Monte Carlo technique. For N stations, there are 12N regression equations derived from observed data and employed to generate simulated streamflows. These are all of the form:

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[2] Beard, Leo R., "Hydrologic Simulation Procedures in Water Yield Analysis," presented at ICID-ASCE Specialty Conference, El Paso, Texas, 3 Dec 1964.

$$X_{ij} = b^{(1)}_{i,j} X_{i-1,j} + b^{(2)}_{i,j} X_{i6} + b^{(3)}_{i,j} X_{i,j-1} + \dots + b^{(j+1)}_{i,j} X_{i,1}$$

$$+ (1-R^2)^{.5} X_r \qquad (1)$$

In which,

X = correlated normal standard deviate

b = beta coefficient

R = sample multiple correlation coefficient

X_r = random normal standard deviate

X_{i6} = total for all stations of the total flow for the 6 months preceding the antecedent month.

The first subscript is the month number, the second subscript is the station number, and the superscript represents the independent variable number. Since coefficients b are beta coefficients relating standard deviates, no regression constant is required.

For a given calendar month, flows are generated for each station in turn. Those for the first station require only the first two terms on the right side of equation 1, those for the second station, the first 3, etc. Integrity of the model is independent of the order in which stations are arranged. Computer programs presently available and results tabulated herein are based on direct multiple regression of streamflow logarithms, which requires simultaneous runoff record at all stations. However, a more general procedure to accomplish the same thing is described in the following paragraphs.

In order to assure that generated data for the model will have both correlation and frequency distribution characteristics of observed data without employing extremely complex transforms, the original data are transformed to a linear system of normal standard deviates. Conversion of streamflows at each station for each month to normal standard deviates is accomplished in the following steps:

a. Each monthly streamflow is incremented by .001 times the normal annual runoff volume for that station, in order to avoid the possibility of large negative logarithms in step b. This quantity is deducted from generated flows in order to avoid bias that would otherwise result.

b. The mean, standard deviation and skew coefficient of logarithms of the incremented flows are computed.

c. The mean logarithm is subtracted from each streamflow logarithm, and the difference is divided by the standard deviation to obtain t.

d. The quotient t, is then transformed to obtain X, the normal standard deviate, based on the computed skew coefficient and the Pearson Type III function. The following approximate equations are used for lack of an exact transform equation:

For t and skew coefficient (g) with like sign:

$$X = t - .12g\,|t|^{1.75} + .16g \qquad (2)$$

For t and skew coefficient (g) with opposite sign:

$$X = t - .22g\,|t|^{3} + .16g \qquad (3)$$

If simultaneous records are available at all stations, beta coefficients in equation 1 can be computed by standard regression procedures. (Because equations 2 and 3 are approximate, regression and beta coefficients are not necessarily identical in this computation). If not all records are simultaneous, beta and multiple correlation coefficients can be based on gross (simple) correlation coefficients between each pair of variables. These must first be checked for mutual consistency to assure that for any three variables, the correlation coefficient between any pair at least equals the product of the correlation coefficients between the other two pairs. If inconsistencies appear, the low value should be increased, because this would have least effect on results. They can then be used as covariance in standard regression procedure. Regression coefficients computed in this manner will be beta coefficients, since all variables are standard deviates. Before testing, the gross correlation coefficients should be smoothed as are mean, standard deviation and skew coefficients, by use of recommended smoothing coefficients in table 2.

If records are not available at a location for which streamflows must be generated, it is necessary to estimate the mean, standard deviation, skew coefficient and the necessary gross correlation coefficients for each month from generalized relationships that can be developed for each region. It is not practical to develop beta and multiple correlation coefficients from generalized studies except through gross correlation coefficients. Methods of deriving generalized relationships are outside the scope of this paper.

Normal standard deviates, generated by use of equation 1 and a normal random number generator, are converted to streamflow logarithms having a Pearson Type III distribution by use of the following approximate equation:

$$X' = M + \left[X + .16g(X^2 - 1)\right] S \qquad (4)$$

After the antilogarithm is obtained, the increment which was added to all flows for the station before analysis is subtracted, and any negative values are set to zero.

Selection of antecedent month and preceding 6 months as independent variables in equation 1 was based in part on the results shown in table 1 and in part on consideration that there sometimes is logically some carry-over influence for several months above that indicated in flows for the antecedent month. Table 1 demonstrates that there would be negligible gain on the average by including also the second antecedent month as a separate variable after the first antecedent month is considered. The carry-over influence is illustrated by the fact that rain at low elevations is often accompanied during winter months by snow at high basin elevations that contributes to runoff in the spring but not necessarily in the late winter.

POPULATION UNCERTAINTIES

The three frequency statistics for each station and calendar month and the gross correlation coefficients used to derive each regression equation are efficient estimators of corresponding "true" values that describe the theoretical population from which recorded and future streamflows come. Errors of estimate for the mean, variance and correlation coefficient are functions of length of record and of theoretical distribution functions as follows:

$$P\left[\frac{(M-\mu)}{x}\right] = P\left[t_{N-1}\right] \tag{5}$$

$$P\left[\frac{(N-1)S^2}{\sigma^2}\right] = P\left[\chi^2_{N-1}\right] \tag{6}$$

$$P\left[\sqrt{\frac{r^2\ (N-2)}{1-r^2}}\right] = P\left[t_{N-2}\right] \tag{7}$$

in which,

P = exceedence probability

M = sample mean

μ = population mean

S = sample unbiased standard deviation

σ = population standard deviation

r = sample simple correlation coefficient

t = Student's t

χ^2 = Pearson's chi-square

By use of random number generation and the theoretical t and chi-square distributions, different values of each statistic are selected each time a new simulation series is generated. This will yield a more realistic sampling of possible future streamflow patterns than would be obtained by use of maximum likelihood estimators only and would in fact apply the principles of expected probability to determinations based on a large number of generated series. This randomization of statistics is applied to computed values before smoothing described in the following section. In order to account for serial correlation of sampling errors, the values of t and chi-square for use in equations 5-7 are serially correlated in the same manner as are streamflow variates.

SMOOTHING OF STATISTICS

Erratic variation of any specific statistic from month to month suggests that these can be smoothed either by curve fitting or by a moving-average technique and thereby improved. Examination of seasonal variations of the statistics, particularly mean logarithm, indicates that a simple curve of annual variation would not be satisfactory. A moving-average is therefore considered most appropriate. It was also found that smoothing of beta coefficients or their squares and the correlation coefficients or their squares would vitiate the multiple regressions to the extent that unreasonable streamflows are generated. Accordingly, smoothing was restricted to the frequency statistics, that is, the mean, variance and skew coefficient. However, smoothing of gross correlation coefficients (covariance) before using them to compute beta and multiple correlation coefficients would be permissible.

The degree of smoothing was determined by split-record analysis. The mean for one month (such as February) in one half of a long record was related by multiple regression to (a) the mean for that month (February) in the other half of the record and (b) the sum of the means in the other half for the preceding and subsequent months (January and March, in this example). The regression was performed separately for each of the 4 statistics and each calendar month over 42 long-record stations in the United States. In this manner, 84 sets of data were obtained for each correlation (by interchanging the record halves).

In effect, this study of smoothing determines what relative weight to give the statistic for the month and the corresponding statistics for the preceding and subsequent months in order to obtain the best estimate of what will occur in the future. Results are shown in table 2. These are average indications for the United States. In selecting adopted values, care was taken not to bias the mean or variance (their coefficients add to 1.00). However, considerable reduction of the skew coefficient (its smoothing coefficients add to .60) is considered warranted, in view of its unreliability and the indication in table 1 that it averages zero nationally.

Thus, means for a given calendar month for generation purposes are obtained by multiplying the computed mean by .84 and adding .08 times the computed means of the preceding and following months. Corresponding smoothing coefficients for the variance are .50 and .25 and for the skew coefficient are .30 and .15. There is no average reduction in mean and variance but 40 percent average reduction in skew coefficient.

TEST OF THE MODEL

The advantage of using a particular model in streamflow simulation can be demonstrated reliably only through split-record tests such as shown in reference 2. However, a test of a multi-station simulation model can be made by comparing all essential statistics of the observed data with corresponding statistics of the generated data, for a large number of operations, in relation to sampling errors of those statistics. Such comparison of frequency statistics and gross correlation coefficients for all essential pairs of variables was made for many of the 42 long records used in deriving the model. These all showed satisfactory comparisons. A typical split-record comparison is illustrated in table 3.

Inasmuch as variables used in the model might not encompass all essential statistics, split-record comparison of series-maximum and minimum streamflows for each calendar month and for various durations were also made for some of the 42 stations. These are considered to support the over-all model adequately. A typical test result is illustrated in table 4.

APPLICATION

Simulation of streamflows is proposed herein for the purpose of reducing some deficiencies in water resources planning, design and operation studies. Its application, unfortunately, adds considerably to the amount of computation involved in such studies. Where electronic computer procedures are already employed, this might not constitute serious additional cost.

Standard methods used in these studies usually include analysis of project operation under recurrence of historical streamflows as modified by "pre-project" changes. Since simultaneous records at all locations considered in a study are usually not complete, some must be estimated from empirical relationships. Usual procedures employed for these estimates ignore many of the complex interrelationships considered in the simulation model. They are consequently not best estimates and are possibly misleading. Also, the record period is usually shorter than desired for project studies.

Missing records for any location would best be estimated by use of a simulation model such as described herein, using regression equations based on all available data to compute specified monthly streamflows, each of which would be based on all pertinent available data for that and preceding months. These would not be used alone as a basis for project studies, but would only be used for making a check on determinations based on simulated streamflows. A computer program for estimating missing monthly streamflows is in preparation in the Hydrologic Engineering Center.

The principal use of monthly streamflow simulation would be to produce a number of properly correlated series of streamflows of length desired for study purposes. These would each be used to make project evaluations. The evaluations could be averaged to obtain a single index of project adequacy, as well as used individually to demonstrate the potential variability of project accomplishments. Compared to over-all study costs for a major investigation, the cost of generating streamflows on a high-speed computer is small. Principal costs would be incurred in employing the values for detailed study. From the findings expressed in reference 2 that storage requirement based on 25 to 50 years of record can easily be in error by a factor of 2 or more, it might be judged that the additional expense would often prove small in comparison to improvement in functional design or operation.

CONCLUSIONS

The model presented herein is believed to satisfactorily accomplish the following:

a. Obtain from a number of streamgage records by regression analysis virtually all pertinent information that bears on the process of monthly streamflow generation at those stations. It is not necessary that records used be limited to simultaneous values at all stations.

b. Generate any number of correlated simultaneous monthly streamflow series of any specified length for any number of stations. These generated series can as likely occur in the future as could a recurrence of historical streamflows. Their use in water resources planning, design and operation studies would permit (1) examination of various representative ways that streamflows can occur in the future and (2) mathematical determination of "expected benefits" of a contemplated project or operation.

The generated series of monthly streamflows are properly interrelated, regardless of the order in which stations are used in the procedure.

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TABLE 1

SUMMARY OF SERIAL CORRELATION AND SKEW LOGARITHMS OF MONTHLY RUNOFF

Sta	$\bar{r}^2$	$\bar{R}^2$	g
102	.30	.31	-.09
103	.24	.24	+.03
105	.15	.16	+.06
107	.20	.21	+.02
113	.18	.17	-.11
120	.18	.20	+.19
121	.27	.28	-.26
221	.28	.30	+.14
301	.18	.17	-.17
303	.17	.19	-.50
311	.29	.28	-.04
320	.22	.23	-.24
323	.40	.41	-.26
326	.24	.25	-.32
335	.32	.33	+.22
403	.40	.40	+.38
404	.41	.42	+.12
405	.30	.31	+.50
501	.72	.72	-.71
514	.58	.59	+.04
523	.24	.25	+.80
533	.38	.38	-.82
534	.25	.25	-.18
605	.38	.39	+.06
806	.34	.34	-.20
808	.47	.51	-.16
901	.52	.52	-.31
1001	.84	.84	-.26
1002	.55	.56	+.03
1107	.51	.51	+.13
1108	.68	.69	+.44
1109	.60	.60	-.16
1111	.52	.54	+.18
1115	.61	.61	-.26
1119	.53	.53	-.05
1123	.48	.49	+.05
1124	.75	.75	+.32
1204	.48	.49	+.40
1303	.51	.51	+.12
1312	.49	.49	+.21
1404	.33	.34	+.04
1409	.33	.33	+.02
Avg	.40	.41	-.01

Note:

All values represent averages of the 12 corresponding monthly values. Definitions are as follows:

r^2 = Serial determination coefficient with antecedent month only

R^2 = Multiple determination coefficient with two antecedent months

g = Skew coefficient

TABLE 2
SMOOTHING COEFFICIENTS BASED ON SPLIT-RECORD REGRESSION

Dependent Variable	Avg	B1	B2	C	B1A	B2A	Determ. coef.	Std. error
Mean, Second half	1.090	.897	.058	-.046	.884	.057	.993	.120
Mean, First half	1.059	.788	.097	.049	.801	.099	.993	.117
Mean, Both halves	1.075	.841	.078	.001	.842	.078	.992	.124
Mean, Adopted				.00	.84	.08		
Variance, Second half	.116	.333	.338	.001	.330	.334	.774	.061
Variance, First half	.119	.360	.247	.014	.421	.289	.775	.060
Variance, Both halves	.117	.348	.288	.008	.376	.311	.760	.061
Variance, Adopted				.00	.50	.25		
Skew, Second half	-.026	.245	.194	.030	.386	.306	.252	.567
Skew, First half	.013	.250	.190	-.035	.397	.301	.242	.581
Skew, Both halves	-.006	.247	.191	-.002	.392	.303	.247	.574
Skew, Adopted				.00	.30	.15		
Determination, Second half	.390	.382	.276	.037	.408	.295	.624	.171
Determination, First half	.401	.364	.255	.037	.416	.291	.592	.177
Determination, Both halves	.395	.372	.265	.038	.412	.293	.607	.174
Determination, Adopted				.00	.50	.25		

Notes:

1. B1 is coefficient of indicated variable for same month, and B2 is coefficient for preceding and following month.
2. B1A and B2A are obtained by multiplying B1 and B2 by a constant to make B1A + 2(B2A) equal 1.000.

TABLE 3

TYPICAL COMPARISON OF STATISTICS OF OBSERVED AND SIMULATED STREAMFLOWS FOUR STATIONS

Period		Distribution			Serial Correlation				Intercorrelation					
		M_4	S_4	g_4	R_1	R_2	R_3	R_4	R_{12}	R_{13}	R_{14}	R_{23}	R_{24}	R_{34}
						OCTOBER								
Observed	1	-.122	.442	-.195	.738	.877	.660	.871	.847	.948	.747	.804	.871	.814
	2	-.197	.390	.110	.739	.903	.684	.821	.860	.950	.745	.878	.843	.844
Simulated	1	-.086	.429	.271	.747	.893	.725	.800	.899	.950	.767	.804	.846	.753
	2	-.110	.284	.042	.811	.834	.513	.542	.870	.969	.813	.850	.974	.851
						JANUARY								
Observed	1	.778	.420	.369	.480	.444	.400	.540	.930	.982	.960	.929	.957	.970
	2	.841	.369	.239	.707	.712	.709	.608	.883	.980	.913	.922	.904	.952
Simulated	1	.872	.449	.242	.219	.192	.127	.050	.896	.989	.954	.922	.958	.972
	2	.910	.423	.750	.879	.808	.874	.775	.904	.978	.945	.938	.901	.967
						APRIL								
Observed	1	1.164	.324	-.162	.847	.929	.866	.786	.867	.940	.724	.922	.871	.878
	2	1.194	.375	-.444	.703	.860	.745	.805	.806	.912	.678	.918	.864	.906
Simulated	1	1.249	.307	-.004	.752	.948	.822	.808	.804	.908	.578	.857	.766	.786
	2	1.286	.354	.195	.822	.854	.834	.792	.903	.950	.865	.950	.923	.968
						JULY								
Observed	1	.055	.600	-.066	.927	.950	.949	.945	.985	.985	.930	.981	.939	.947
	2	.065	.531	-.245	.936	.954	.951	.941	.981	.984	.943	.983	.957	.969
Simulated	1	.129	.610	.195	.892	.942	.926	.935	.991	.976	.890	.981	.913	.921
	2	.255	.419	-.343	.844	.916	.848	.818	.967	.968	.893	.963	.946	.952
						ANNUAL								
Observed	1	1.883	.329	-.063	.216	.276	.171	.341	.961	.974	.942	.970	.975	.975
	2	1.939	.300	-.314	-.032	.207	.027	.143	.938	.981	.934	.958	.960	.977
Simulated	1	1.951	.310	.365	.141	.156	.090	.102	.975	.986	.949	.985	.975	.973
	2	2.041	.280	-.242	-.435	-.268	-.367	-.143	.939	.970	.874	.971	.967	.951

TABLE 4

TYPICAL COMPARISON OF EXTREME VALUES
OBSERVED AND SIMULATED STREAMFLOWS
FOUR STATIONS

		Station 1				Station 4			
		Recorded		Simulated		Recorded		Simulated	
		1	2	1	2	1	2	1	2
Oct	Max	119	63	61	64	6	2	6	4
	Min	7	7	6	8	0	0	0	0
Jan	Max	260	224	376	516	58	33	89	96
	Min	12	12	10	12	2	1	1	2
Apr	Max	449	352	429	448	46	46	53	100
	Min	73	118	98	93	2	2	5	4
July	Max	1,000	402	846	404	22	7	27	11
	Min	13	25	15	67	0	0	0	0
Year	Max	3,899	3,272	4,014	3,111	340	251	363	363
	Min	392	659	529	838	14	16	26	24
6-mo	Max	3,578	2,858	3,535	2,436	297	220	339	343
	Min	42	57	60	78	1	0	1	3
54-mo	Max	11,980	10,680	12,329	10,393	973	833	882	964
	Min	4,462	4,803	3,920	5,817	173	196	221	292

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