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14. ABSTRACT
Techniques developed in the Hydrologic Engineering Center of the Corps of Engineers for reconstituting missing portions of monthly streamflow data are being tested by application in the Pacific coastal area of Peru. To develop the coordinated set of streamflow records, a base period of fifty years was selected, and missing monthly streamflow data were estimated at teach of the sixty gaged locations, using regional analysis and correlation with appropriate physical and hydrologic characteristics. From this complete set of streamflow records, concurrent values for each of the forty remaining ungaged locations will be estimated. Monthly streamflow quantities are produced to enable the Peruvian government to evaluate water resources developments along the western coast, and provide information for comparison of alternative schemes of development.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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ESTIMATING MONTHLY STREAMFLOWS WITHIN A REGION[a]

By Leo R. Beard, F, ASCE,[1] Augustine J. Fredrich, M, ASCE,[2]

and Edward F. Hawkins, AM, ASCE[3]

INTRODUCTION

Techniques developed in The Hydrologic Engineering Center of the Corps of Engineers for reconstituting missing portions of monthly streamflow data (2) are being tested by applications in the Pacific coastal area of Peru. This is a cooperative project with the Oficina Nacional de Evaluacion de Recursos Naturales (ONERN) in Lima, Peru, as a part of the International Hydrological Decade program. The objective of the study is to develop a coordinated set of monthly average streamflows for about 120 locations in the 52 drainage basins of western Peru shown in figure 1.

Peru's western coast is characterized by great variation in physical, meteorologic, and hydrologic factors. Although only one of the basins exceeds 4,000 square miles in size and many are less than 2,000 square miles, elevations range from sea level to more than 12,000 feet in almost all basins. The higher elevations in all basins receive relatively large amounts of precipitation, between 30 and 100 inches per year; but at the lower elevations, which comprise more than 50 percent of the study area, the average annual precipitation is less than one inch.

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[1]Director, The Hydrologic Engineering Center, Corps of Engineers, Sacramento, California,

[2]Chief, Research Branch, The Hydrologic Engineering Center.

[3]Engineer-in-Charge, IHD Project, The Hydrologic Engineering Center.

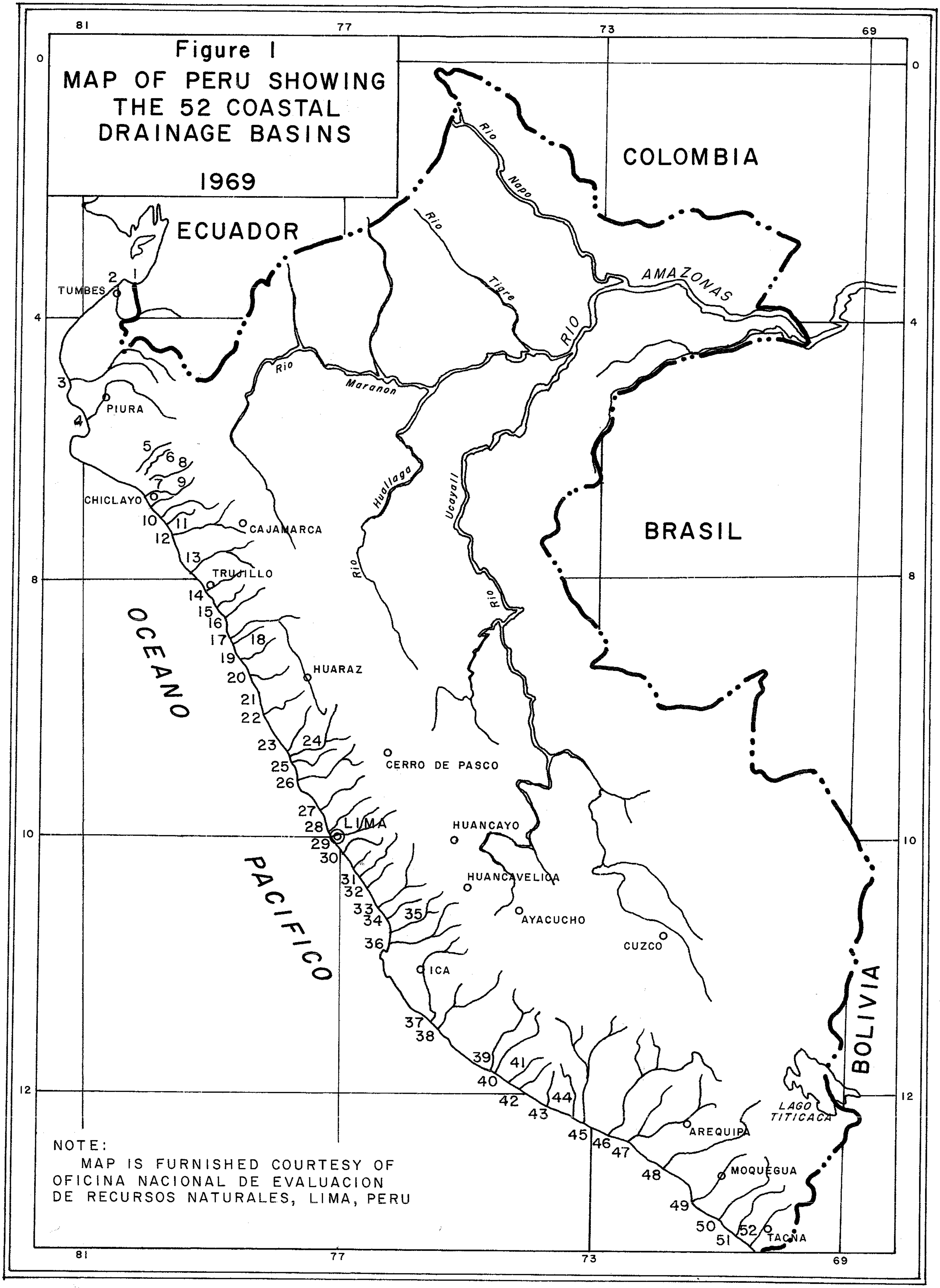

Figure I
MAP OF PERU SHOWING THE 52 COASTAL DRAINAGE BASINS
1969

NOTE:
MAP IS FURNISHED COURTESY OF OFICINA NACIONAL DE EVALUACION DE RECURSOS NATURALES, LIMA, PERU

To develop the coordinated set of streamflow records, a base period of 50 years was selected, and missing monthly streamflow data were estimated at each of the 80 gaged locations, using regional analysis and correlation with appropriate physical and hydrologic characteristics. From this complete set of streamflow records, concurrent values for each of the 40 remaining ungaged locations will be estimated. The completed study will produce monthly streamflow quantities that will enable the Peruvian government to evaluate water resources developments along the entire western coast and will provide consistent information for comparison of alternative schemes of development.

PROCESSING OF BASIC DATA

In most regions of sparse hydrologic data, even the information that does exist is largely unavailable, because there is no central data repository. In a study of the nature described herein, it is not feasible to collect data from individual stations, and consequently such data must be ignored. It must be kept in mind, however, that estimates of missing data can be replaced if and when observational data become available. Fortunately, a large portion of the hydrologic records that exist in Peru have been assembled and are available in the files of Government agencies. Even these must be examined carefully, however, to assure that decimal-place and other types of errors do not exist and that zero values are actual observations and not simply missing data.

The original compilation of daily streamflow data at about 80 locations and monthly precipitation data at about 75 locations were obtained, checked, and punched on IBM cards for permanent use. Monthly average streamflows were computed and stored separately. These monthly streamflow values were adjusted to natural conditions, insofar as possible, by adding the amount of irrigation diversion that occurs each month above each station. These irrigation quantities are estimated on the basis of irrigated acreage and relationships developed for locations where gaging stations exist on diversions or on a river above and below diversions. A comprehensive tabulation of average monthly diversion quantities for all pertinent river regions is being prepared for use in estimating future streamflow depletions.

GENERAL PROCEDURE

Values of monthly streamflow that are missing from the records are estimated by use of concurrent monthly streamflows recorded at other locations, taking into account the degree of correlation between locations.

While it is usual practice to select one long record for such correlation, it is considered that this practice would often ignore useful information at other locations and important correlations with other locations. Accordingly, techniques used in this study include the simultaneous correlation with all pertinent locations where records exist for each month of missing data, insofar as this is feasible. This involves the use of multiple linear regression analysis. In order to preserve the degree of correlation that exists among all stations, a random component is added to each estimated value. The importance of adding this random component is illustrated in figure 2, which is an example of simple linear correlation. It is apparent by observation of figure 2 that, if a random component is not added, the range of estimated values becomes smaller than the range of recorded values at the same station, and the correlation of the estimated values with corresponding observed values at the other station is perfect. Either of these erroneous results could seriously affect the design of water resource projects. Accordingly, while a least-square-

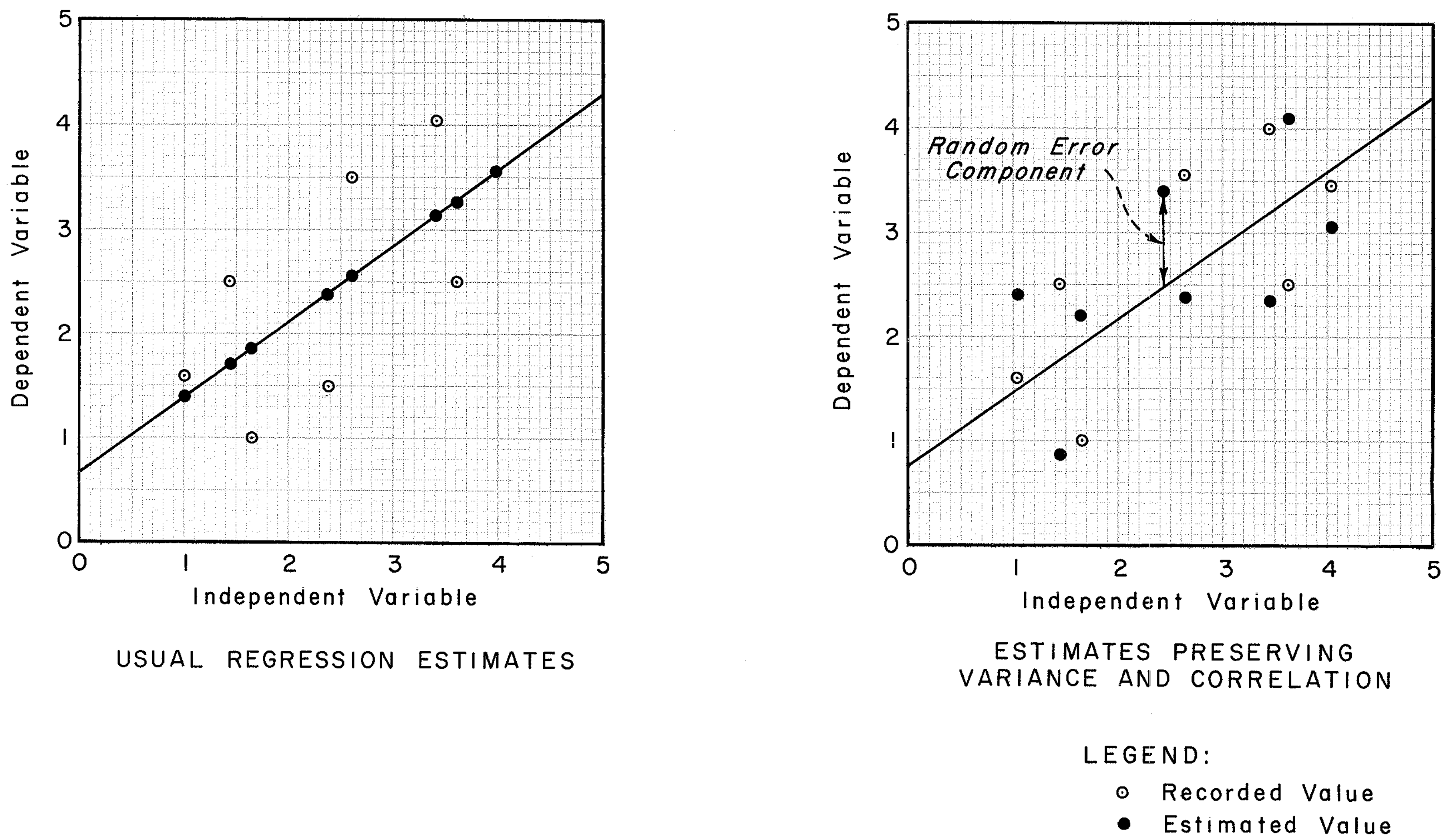

Figure 2

DATA RECONSTITUTION TECHNIQUE

error estimate of an individual value (without a random component) is the best estimate of that isolated value, the best set of estimates does not consist of the set of best individual estimates.

Inasmuch as multiple regression analysis is based on the assumption that all variables are distributed in accordance with the Gaussian normal distribution, the logarithms of streamflow and precipitation quantities are used as variables. It has been observed generally that logarithms of these quantities are approximately normally distributed. In order to avoid the problem of computing a logarithm of zero flow and in order to diminish the undue influence of very small flows during drought periods, a small increment equal to .1 percent of the average annual flow or precipitation is added to the value for each month before the logarithm is computed. The mean and standard deviation of these logarithms of incremented flows are computed for each month at each station. Those computed from short records are adjusted by use of data at a nearby long-record station. Standardized quantities are then computed by subtracting the mean from each logarithm and dividing by the corresponding standard deviation.

The general equation used for computing an individual monthly streamflow is as follows:

$$X_{i,j} = \beta_{i,1} X_{i,1} + \beta_{i,2} X_{i,2} + \ldots + \beta_{i,j} X_{i-1,j} + \ldots + \beta_{i,n} X_{i-1,n} + Y(1-R^2)^{1/2} \qquad (1)$$

where:

$X_{i,j}$ = Logarithm of incremented average monthly streamflow, standardized to zero mean and unit variance

$\beta_{i,j}$ = Beta coefficient

i = Month sequence number

j = Station sequence number

n = Total number of stations

Y = Random variate from normal distribution with zero mean and unit variance

R = Multiple determination coefficient

In order to maintain a reasonable number of stations for each computation, stations are grouped in sets of 10 or less. The manner of grouping stations is extremely important, because it is important to include in each successive group as much information as possible that is pertinent to the computation of missing flows for each station in that group. Thus, in general, the longest-record stations for the entire study would be included in the first group. Each successive group would contain at least one of these stations, including flows already estimated for that station.

To the knowledge of the writers, procedures are not yet available in mathematics literature for performing regression analyses using incomplete data sets. The following procedures were devised in the HEC for this purpose and have been incorporated into a generalized computer program (4). (Some attendant difficulties are discussed in the following section.)

(1) Compute simple (gross) correlation coefficients for each month between values at each station and (a) concurrent values at each station and (b) preceding values at each station. This gives $2n^2$ coefficients for each month, which are stored for use.

(2) The correlation matrix needed for reconstituting a missing value for a given station and month is formed of correlation coefficients between

values for that station and that calendar month and values for each other station and (a) the same calendar month, if the other station has a value for that month and year, or (b) the preceding calendar month, if the current-month value for the other station is missing (The value for the preceding month is either recorded or already reconstituted).

(3) Beta coefficients for the regression equation and the determination coefficient are then computed from the correlation matrix in exactly the same way that regression coefficients and the determination coefficient are computed from a covariance matrix.

Computation of missing flows in each group is accomplished by searching the values at each successive station, starting with the earliest month for which record exists at any station in the group, and proceeding to subsequent months, reconstituting missing values as they are encountered. As soon as a month of missing flow at a station is encountered, a regression equation is then computed that relates that flow to concurrent flows at other stations, or to the preceding month's flows if the concurrent flow is missing. By application of equation 1, the missing value is computed. Reconstituted values are identified in the computer printout, as illustrated in Table 1.

MATHEMATICAL PROBLEMS

Inasmuch as there are missing values in the records, each regression equation must be based on an incomplete data set. In order to make maximum use of available information, a correlation matrix is constructed, each element of which is the correlation coefficient between all common data for the two variables. Since not all correlation coefficients are based on simultaneous data, it is possible that the resulting correlation matrix will be inconsistent within itself. While it is possible to devise some means of changing selected coefficients to create a consistent matrix, this might be highly objectionable. It is important that the data used in regression analysis be consistent with the correlation matrix upon which the equation is based. Otherwise, some highly erratic estimates can result.

There is no existing mathematical technique for managing this particular problem. However, it is considered that the data used in the regression equation must also be used in computing the correlation matrix. (It will be noted that this is inconsistent with accepted practice.) The requirement is not vital where large samples exist, but can be critical when the regression equation is based on a small sample.

Rather than to modify the correlation matrix when it is found to be inconsistent, it is considered that one or more of the independent variables should be omitted from the regression equation for that month and station. The variable omitted is that having the smallest partial correlation coefficient. This process is repeated until a consistent matrix occurs.

As soon as each missing item is reconstituted, the correlation matrix for the entire set of stations is modified to account for that item before proceeding to the next computation. This involves tremendous amounts of computation, but is absolutely necessary in order to assure mathematical integrity.

RELIABILITY OF RECONSTITUTED VALUES

The multiple correlation techniques applied in this study were used in order to obtain maximum reliability of reconstituted values. While they should provide estimates of missing values that are considerably superior to those obtained by traditional means, there are still some questionable assumptions

TABLE 1
RECORDED AND RECONSTITUTED FLOWS
(IN CUBIC METERS PER SECOND)

STA	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
60	1911	36.15E	57.56E	54.54E	34.98E	17.59E	14.91E	14.33E	9.57E	13.26
60	1912	29.12	35.48	41.42	31.35	20.18	15.39	14.82	13.97	13.16
60	1913	48.42	62.68	89.22	24.55	20.18	15.89	15.22	12.97	9.46
60	1914	34.32	29.48	64.32	123.25	25.98	19.49	12.92	10.67	10.46
60	1915	73.62	53.18	48.82	42.15	19.68	16.69	14.72	13.87	17.76
60	1916	66.64	75.46	53.25	43.89	30.39	18.17	15.00	10.81	10.91
60	1917	46.33	32.16	41.37	44.25	16.74	11.03	9.93	9.43	11.96
60	1918	60.46	89.09	80.78	47.21	28.87	23.59	18.08	15.63	15.68
60	1919	30.78	54.76	61.12	44.88	22.37	17.11	13.94	11.45	10.67
60	1920	54.22	50.12	72.70	57.87	28.40	18.16	12.46	9.91	10.18
60	1921	52.24E	49.07E	59.66E	43.76E	26.42E	17.78E	16.79E	14.66E	12.92E
60	1922	52.34E	58.96E	80.86E	61.85E	26.89E	19.13E	17.61E	12.51E	11.65E
60	1923	34.75E	48.03E	55.75E	49.65E	27.87E	19.50E	15.43E	11.90E	10.61E
60	1924	74.58E	94.79E	54.47E	41.62E	27.89E	15.89E	13.94E	11.53E	10.88E
60	1925	41.85E	53.35E	43.37E	49.11E	25.49E	17.42E	22.51	13.82	13.36
60	1926	18.07	35.12	63.35	46.39	18.01	15.95	13.82	10.93	11.38
60	1927	50.04	81.34	58.67	37.45	20.00	15.25	13.86	11.27	12.10
60	1928	30.64	65.25	85.98	46.67	19.81	15.36	13.48	11.22	11.10
60	1929	31.30	109.32	56.27	33.51	16.86	13.11	11.76	11.36	15.66
60	1930	86.97	82.87	86.93	38.32	20.50	16.44	14.77	12.35	11.22
60	1931	30.50E	44.40E	68.66E	40.14E	29.62E	22.52E	10.19	8.43	8.35
60	1932	44.33	79.22	50.61	38.60	22.45	17.42	16.88	12.68	11.60
60	1933	76.38	79.70	89.83	77.04	41.93	17.55	14.60	11.59	10.55
60	1934	35.80	42.58	65.17	48.49	28.02	20.47	16.54	13.22	12.33
60	1935	27.88	35.89	67.97	43.86	23.24	18.77	16.54	13.19	11.41
60	1936	51.82	40.99	40.86	28.50	25.80	18.92	16.25	13.87	12.18
60	1937	18.75	21.90	37.73	28.40	20.05	15.93	13.54	11.16	9.82
60	1938	24.77	54.98	47.79	45.20	25.76	17.97	13.26	10.81	9.61
60	1939	32.86	48.79	75.99	61.45	28.31	20.37	14.46	12.20	12.20
60	1940	71.32	53.04	73.83	47.30	27.35	22.22	18.88	15.61	12.54
60	1941	54.45	73.45	86.26	31.72	25.52	16.36	14.54	13.69	13.67
60	1942	40.35	64.52	63.58	36.72	30.61	18.97	15.28	13.13	12.47
60	1943	35.59	82.01	73.38	58.22	23.69	19.50	16.93	14.18	13.76

Note: E denotes an estimated value.

that bear on the validity of estimated values. The most important assumption is that information contained in the available data adequately represents the true conditions that produce streamflows. Regression coefficients based on short records can be considerably in error, particularly when a large number of variables is used. Erratic results of this nature are guarded against to some extent by eliminating variables when beta coefficients exceed 1.5 or are smaller than -.5. (If negative correlation exists between the given variable and the dependent variable, the limits are -1.5 and .5.) The assumptions of linearity of correlation and normality of the logarithmic distribution, are subject to question, and their influence on the results is difficult to measure.

Because of the various sources of possible error, all generated flows are examined carefully to assure that they are reasonably consistent with all recorded flows. This test is facilitated by tabulating the maximum and minimum recorded and reconstituted flows for each month and for various durations of one month and longer.

ESTIMATES FOR UNGAGED LOCATIONS

In order to estimate flows for locations where no records exist, it is necessary to relate certain characteristics of monthly streamflows to characteristics of river basins (1, 3). In the case of the coastal streams of Peru, where all runoff orginates in the higher mountains and practically all diversion occurs in the coastal plain, this problem is somewhat simplified. While studies to correlate runoff and basin characteristics have not yet been conducted, it is planned to relate average monthly streamflows to the drainage areas within each thousand meters of elevation and to the general geographic location of the basin.

Weighting factors for each elevation zone will be developed, and coefficients for each river basin will be derived by coordinating observed coefficients in relation to latitude of the basin. Monthly flows for ungaged locations will then be established on the basis of these coefficients and recorded and reconstituted streamflow at nearby locations, adjusted for the estimated effects of diversions above the various stations.

SUMMARY

The techniques used in this study for estimating each individual monthly streamflow value are considered to have important advantages over traditional techniques of using only a single station and standard correlation techniques. In addition to increased reliability, the techniques described herein preserve the natural variance of streamflows and the natural serial and inter-station correlations. There are some serious mathematical problems that have not been solved, and consequently considerable care must be exercised in examining estimated values before they are adopted for use. Inasmuch as a random component is required to preserve variance and correlation, it must be recognized that estimated values do not constitute a unique solution, nor do they reflect a "best", in the least squares sense, estimate of the specific missing events. However, the estimated and recorded or adjusted flows do constitute a data set which preserves, to the maximum extent possible, the spatial and temporal streamflow characteristics and thus fulfill a primary need for hydrologic data for regional water resources planning and development.

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ESTIMATING MONTHLY STREAMFLOWS WITHIN A REGION

KEY WORDS: Computer programs; Hydrologic data; Hydrology; Mathematics; Peru; Regional analysis; Regional planning; Regression analysis; Statistical analysis; Streamflow; Synthetic hydrology

ABSTRACT: Estimates of monthly streamflow data for use in regional water resources planning and development studies are considered to be much more useful if techniques which preserve the natural variance of streamflows and the natural serial and inter-station correlations are employed. A technique for estimating missing monthly streamflow data is described and a proposed method for estimating monthly streamflow for ungaged areas is discussed. The estimation of missing data depends on statistical analysis and multiple correlation of streamflow characteristics of recorded data at each station within a selected region and on the use of a random component required to preserve variance and correlation characteristics of the data. The statistical analyses and correlation studies have been conducted by use of a generalized computer program. Some mathematical problems encountered during the study are discussed and the need for review of the estimated and recorded data sets is emphasized.

Summary for Civil Engineering

A computerized technique for obtaining estimates of monthly streamflow data for use in regional water resources planning and development is described. The technique is based upon the need for preserving natural variance of streamflow and for maintaining natural serial and inter-station correlations within a given region.

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