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14. ABSTRACT
Methods used for extending available hydrologic information in time and space, most of which involved the use of electronic computers, are described. The incremental value of a single streamflow records at the site of a major reservoir far exceeds the cost of the record, even after more than 100 years of record and even for relatively stable streams. The maximum use of hydrologic information in short records for design purposes can be made by an elaborate analysis of the statistical characteristics of recorded streamflows and use of statistics to generate long sequence. These sequences can be generated at the gaged locations or, through regionalized studies, at ungaged locations. A comprehensive computer program is available in the Hydrologic Engineering Center, US Army Corps of Engineers, Davis, California for analyzing monthly streamflow characteristics, estimating missing values of monthly streamflows at short-record stations based on the longer-record stations in the vicinity, and generating any number of streamflow sequences of any length for use in design.

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MAXIMUM UTILIZATION OF SCARCE DATA IN HYDROLOGIC DESIGN[1]

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INTRODUCTION

During the early development of electronic computers, principal uses were associated with the processing of large quantities of data. Now there is an important application of computers to work associated with scarce data. This includes elaborate analyses of statistical characteristics of available data and correlations between available data and associated phenomena. Methods that are used for extending available information in time and space, most of which involve the use of electronic computers, are described in this paper.

VALUE OF STREAMFLOW DATA

All hydrologic evaluations require the use of some data recorded at locations pertinent to each problem or at associated locations as near to the problem area as possible. The minimum amount of recorded information required for a satisfactory analysis depends on the nature of the problem as well as the general statistical features of pertinent hydrologic phenomena. Generally speaking, problems involving the development of available water supplies to a high degree require more information than those involving a

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fractional use of available resources. In areas where streamflows are erratic, much more information is required than for areas of stable streamflow.

The Hydrologic Engineering Center of the Corps of Engineers and the U.S. Geological Survey are cooperating on a research project to examine the value of increasing streamflow data in time and space. Initial studies examined the value of streamflow data for reservoir design on the premise that correlation studies and stochastic analyses are not made. It was found that the incremental value of a single streamflow record at the site of a major reservoir far exceeds the cost of the record, even after more than 100 years of record and even for relatively stable streams. Of course, the value increases as the stream regimen becomes more erratic and particularly for those cases where records are short. In these and associated studies, it has also been found that there is considerable gain in design reliability by use of regional correlation studies and by use of stochastic generation processes for both gaged and ungaged locations. However, the transfer of information in both time and space is ordinarily a small fraction of the total information in the basic record.

All experience to date indicates that there is no complete substitute for obtaining data at the specific locations required for analysis and for as long a period as possible. However, when a design is required, it is necessary to make the best use of whatever information is available. The procedures described in the following sections have been found by The

Hydrologic Engineering Center to be of considerable practical use in this regard.

ADJUSTMENT OF RECORDED DATA

In the management of hydrologic data, it must be recognized that each record to be analyzed must be consistent in time and must conform to conditions specified in the problem. In many cases, construction of reservoirs, diversions and other works at upstream locations might have affected the recorded streamflows during part of the period of record. The recorded flows must then be adjusted to a uniform condition. In many studies, it is desirable to adjust to natural conditions. Such natural flows can then be used in analyzing the effects of both the new and old projects in combination. One advantage of adjusting to natural conditions is that the statistical characteristics of the flows can then be studied with some confidence that they would conform to natural laws.

In many cases, it might not be feasible to adjust flows to natural conditions. This can be because upstream improvements are very numerous or that the manner in which they affect flows is unknown. In such cases, flows are adjusted to a specified uniform condition that would be more convenient and sufficiently dependable for the analysis. Often this is the pre-project or non-project condition that would prevail in the future if the proposed new project would not be constructed.

In studies of water supply, it is usually adequate to study monthly average streamflows. The time lag between locations on a stream is usually small compared to one month, and is ignored when making adjustments. Such adjustments are then made simply by adding diverted monthly average flows and monthly storage changes to the recorded monthly average flows at the downstream point. In the case of short-period studies such as for flood control, detailed studies of time-delay and storage effects might be required.

ESTIMATION OF MISSING DATA

Probably the greatest gain that can be obtained in extending hydrologic data in time and space is through correlation of data within a region, extending the shorter records to the full length of the longest record. These estimations must take into account the differences of statistical characteristics between locations, the intercorrelations that exist between locations and the persistence effects that prevail in the different locations.

Extension of short records by transfer of information from longer records is of value to the extent that a correlation exists and to the extent that the nature of the correlation or non-correlation can be determined. The degree of non-correlation is a function of phenomena that affect one location and not the other or that affect the two locations differently. This non-correlation can be important in design, because it is through non-correlation that stability can be given to a regional water resources development. Hopefully, extreme droughts or other extreme phenomena will not occur simultaneously at all locations, and this is only assured when there is some degree of non-correlation. Accordingly, it is essential in the estimation of records for use in multiple-site analyses to include an appropriate degree of non-correlation as well as a degree of correlation.

In order to maintain pertinent correlations and non-correlations, estimates of missing data must be based on all pertinent data that have been recorded at other locations, to the extent practicable. This requires elaborate multiple correlation studies, along with complete statistical analysis of data at all locations. Such an elaborate analysis is not possible without a relatively large and fast electronic computer.

A computer program has been developed in The Hydrologic Engineering Center that will accept monthly streamflow data at a large number of locations, automatically compute the statistical and correlation data required, and reconstitute all missing data. The persistence characteristics and inter-correlations between stations are preserved by the statistical-model and the non-correlation is preserved by including an appropriate random quantity in each estimated streamflow. The essential features of this computer program were described in reference 1.

GENERATION OF SYNTHETIC SEQUENCES

Although short records do not contain many extreme events and critical sequences that might occur in the future, they do reflect the statistical characteristics of hydrological phenomena, and these can be used to synthesize different events and sequences that might occur in the future. The pertinent statistics based on short records are subject to errors of estimate, primarily because small samples of data can be highly non-representative of the large body of future events that they must be assumed to represent. Consequently, synthetic sequences based on short records are not as valuable as the actual records of equal length. They simply present in usable form the detailed data available in the record, which is usually not efficiently used in traditional methods of analysis.

By use of the computer program discussed in the preceding section and described in reference 2, all pertinent frequency and correlation statistics of monthly streamflows at a number of locations are computed. These statistics can then be used to generate any number of sequences that can realistically occur in the future. They can be used in the design of water resource improvements in exactly the same manner as historic recorded sequences are used.

The general equation used for generation of synthetic streamflow sequences is as follows:

$$X_{i,j} = a + b_{i,1} X_{i,1} + \cdot \cdot \cdot \cdot b_{i,j-1} X_{i,j-1} + b_{i,j} X_{i-1,j} + \cdot \cdot \cdot \cdot + b_{i,N} X_{i-1,N} + \sqrt{1-R^2}\, X_R$$

where

- X = Logarithm of streamflow
- b = Multiple regression coefficient (from recorded data)
- i = Sequence number of month
- j = Station number in order of generation
- R = Multiple correlation coefficient
- X_R = Random error component

ESTIMATES FOR UNGAGED AREAS

A standard technique for obtaining regional sequences of streamflows at ungaged locations is to multiply recorded streamflows at a nearby location by an appropriate ratio. Such a ratio is often obtained as a ratio of respective tributary area sizes, including a factor for difference in normal precipitation, where important, or by other means such as regional comparison of observed runoff quantities. The technique could also be applied to synthetic streamflows that were generated for a nearby location. However, it would generally be better to transfer the basic statistical characteristics to an ungaged area, rather than to transfer the runoff quantities. A difficulty encountered is that there are a great many statistics required by most generating models to describe completely the streamflow characteristics at any location. Some work has been done in coordinating the many required statistics into a few generalized statistics. This work is described in references 3 and 4. The former reference describes detailed techniques for generating monthly streamflow data at a number of ungaged locations simultaneously. The generalized computer program, reference 2, contains routines for automatically computing generalized statistics and for using the generalized statistics to generate any specified number of years of synthetic streamflows for ungaged areas.

APPLICATIONS IN PERU

The Corps of Engineers has undertaken the preparation of a report entitled "Hydrologic Engineering Methods for Developing Project Design Criteria" as part of its contribution to the United States' program for the International Hydrological Decade. As an integral part of the Corps of Engineers project The Hydrologic Engineering Center is conducting cooperative hydrologic studies with government agencies in Peru and Guatemala. These studies are designed to test the validity of the proposed methods under realistic conditions of scarce data, evaluate the usefulness of the proposed methods, ascertain the necessity for additional methods, and develop in the foreign participants confidence in the methods.

The cooperative studies in Peru are primarily concerned with development of a consistent set of streamflow data for the entire western coastal area of Peru. This consists of adjusting existing records - which range from five to fifty years in length - to account for relatively extensive modifications of the natural flow at about 150 locations in the 52 river basins that drain into the Pacific Ocean. When the adjustments are completed so that the data represent natural streamflow conditions, all missing streamflow data are estimated on a monthly basis using the previously described techniques in order to obtain a complete record of, say, 50 years length at each of the 150 stations. Finally, complete monthly records will be estimated at 20 to 25 points of interest where no streamflow data are presently available.

Available records consist largely of data compiled to meet specific requirements of various governmental, local, and private agencies. Although there are some continuous records more than 50 years long, there is evidence that no systematic approach to obtaining representative hydrologic data was utilized until the early 1960's. Consequently, the areal distribution of available data is rather poor, with accessibility and availability of observers being the factors which predominated in the selection of gaging sites. Furthermore, there has been a very limited amount of documentation of the conditions under which the data were collected and in some cases it is apparent that significant alterations in the regime have occurred at one or more points in the records with no attendant explanation.

The adjustments that must be made in the recorded data are of two types. First, the data must be examined on a station-by-station basis to identify discrepancies in the data which are inconsistent with nearby stations and known hydrologic conditions. Since these discrepancies are frequently unexplained in the records, it is necessary to make adjustments by requesting additional information from the entity which maintains the record, by correlation with other hydrologic data such as precipitation or snowpack, by correlation with other nearby stations, and by engineering judgment. Data which are obviously erroneous may be treated as missing data and thus be estimated at a later time in the study. The second type of adjustment is the removal of the effect of man-made alterations in the streamflow data itself. Since the model is oriented toward natural phenomena, it is necessary to use, insofar as possible, data which do not include the effects of regular and/or systematic upstream alterations such as might exist where upstream reservoirs or significant upstream diversions have modified the natural streamflow. The necessary adjustments are to be made by correlation analyses which consider precipitation, irrigated acreages, area-elevation relationships, and other physical and hydrologic parameters. Monthly records for the ungaged locations included in the study are estimated by regional correlations of streamflow and physical and hydrologic variables. These data are needed for engineering projects that are either under design now or are to be developed in the relatively near future.

APPLICATIONS IN GUATEMALA

The initial cooperative studies for Guatemala are designed to evaluate selected hydrologic aspects of a specific project, the proposed Atitlan hydroelectric project. It is anticipated that the project will consist of the development of hydroelectric generating facilities at three locations and of structures to divert water from three adjacent rivers into Lake Atitlan, a relatively large natural lake about 1560 meters above msl. Hydrologic and meteorologic records in the vicinity of the project are generally of good quality although not of very long duration. Some precipitation data are available from 1928 to present, but streamflow data in this area are not available prior to 1962. Other pertinent hydrologic data range in availability from non-existent in the case of sediment samples to isolated and short-term observations in the case of evaporation data.

The performance of the systems analysis studies contemplated will require consistent monthly and daily streamflow data at each diversion site. It is anticipated that both the historic record and several generated sequences will be studied to develop a plan of operation. To avoid bias and to insure a realistic operation plan it is essential that the streamflow data be available at all pertinent locations for the same historic period, that the data reflect the true contemporaneous differences from location to location, and that the data reflect as nearly as possible the hydrologic conditions which result at each location from climatological factors that affect all locations simultaneously. Estimation of the missing data and generation of additional data by the streamflow simulation model and by correlation techniques will produce data possessing these characteristics.

Sediment problems which are expected to require study include: deposition in the vicinity of diversion structures and inlets, conveyance through tunnels and pumps, and deposition into the naturally clear Lake Atitlan. Due to the absence of sediment transport and deposition data, little is known about potential sediment problems. An intensive sampling program has been recommended and it is expected that the results can be used in correlation studies to estimate sediment deposition volumes and the approximate locations of deposits.

Since the lake has no natural surface outlets, its level is dependent upon evaporation from its 128 Km^2 surface area and upon seepage, apparently from the southern boundary of the lake. Although there are only limited data concerning seepage, there are good, relatively long-term records of lake levels and it is believed that correlation studies relating seepage to surface elevation might be useful together with evaporation studies in estimating losses which occur under project conditions.

System analyses utilizing HEC computer programs developed for that purpose and the streamflow and loss data developed earlier in the study are expected to provide estimates of the output of the project for use by the Guatemalan government in evaluating the financial feasibility of the project and it is expected that comparison of alternative operating schemes will lead to determination of an optimal or near-optimal plan of operation for the project.

CONCLUDING COMMENTS

The maximum use of hydrologic information in short records for design purposes can be made by an elaborate analysis of the statistical characteristics of recorded streamflows and use of such statistics to generate long sequences. These sequences can be generated at the gaged locations or, through regionalized studies, at ungaged locations. The computations involved are too elaborate for accomplishment without a large electronic computer. A comprehensive computer program is available in The Hydrologic Engineering Center for analyzing monthly streamflow characteristics, estimating missing values of monthly streamflows at short-record stations based on the longer-record stations in the vicinity, and generating any number of streamflow sequences of any length for use in design.

The technique is still in the development stage. Although many streamflows have been generated satisfactorily for a great many regions, their application to design has been limited, principally because there has not been sufficient demonstration of their validity. Some questions of reliability still exist, and considerable development work in this area remains to be done. The reliability of generated sequences is generally good in humid regions where flows are more stable and can be considerably less dependable in arid regions where flows are highly erratic.

The techniques used in this process extract a maximum amount of information from the available data and extend the information in space and in time. They do not create information, but simply make the available information most useful for design. Although techniques already developed can aid greatly in design, it is expected that future developments and experience in their application will greatly expand the utility of these techniques.

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