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14. ABSTRACT
The purpose of this paper was to discuss briefly and very generally the nature of hydrologic engineering problems that could be solved through application of statistics and to examine the basic concepts involved in the application of statistics to such problems. The importance of applying statistics to such problems. The importance of applying statistics to a complete decision process, rather than to an incompletely separable link of that process, was emphasized. Hydrostatistics which have historically been concerned primarily with the determination of the probability or frequency of events and the correlation or interrelation among events, were discussed. It was said that in most cases of hydrologic design, it is traditional to select a design criterion that expresses the adequacy in terms of probability of exceedence. An example of a water supply reservoir that might be designed for a drought that would be exceeded once in twenty-five years was given. Discussions were based upon the objective of determining expectation over a long period of operation of a specific project design, rather than evaluation of the probability of hydrologic events independent of any design. These included probability of a single event, indirect probability determinations, coincident probability determinations and complex probability problems.

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HYDROSTATISTICS - PRINCIPLES OF APPLICATION[1]

by

Leo R. Beard[2]

INTRODUCTION

There is growing concern with the gap of several years that exists between development of engineering techniques in the academic community and the application of these techniques to real problems in the so-called practicing profession. One of the reasons for this gap is that the real nature of problems in planning, design and operations studies is not communicated from the field to the academic community. Consequently, many outstanding techniques are developed that are not readily applicable to real problems. This is particularly true in the field of hydrostatistics. It is the purpose of this paper to discuss briefly and very generally the nature of hydrologic engineering problems that can be solved through application of statistics and to examine the basic concepts involved in the application of statistics to such problems. The importance of applying statistics to a complete decision process, rather than to an incompletely separable link of that process, is emphasized.

HYDROSTATISTICS

Hydrostatistics has historically been concerned primarily with the determination of the probability or frequency of events and the correlation or interrelation among events. A great deal of literature exists on the nature of frequency distributions, multiple regression techniques and multi-variate and

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component analysis. The recent increased activity in stochastic hydrology has greatly expanded the field of hydrostatistics and puts greater emphasis on the exact nature of multi-variate distributions and serial correlation. It promises to improve present solution techniques and to provide solutions to problems that have heretofore been difficult or impossible to solve.

APPLICATION OBJECTIVES

In many and probably most cases of hydrologic design, it is traditional to select a design criterion that expresses the adequacy in terms of probability of exceedence. For example, storm drain laterals might be designed (more or less arbitrarily) for the flow that would be exceeded once in five years, or a water supply reservoir might similarly be designed for a drought that would be exceeded once in 25 years. It is suggested that such criteria should be replaced as soon as possible by more fundamental criteria such as a threshold criterion for incremental benefits in relation to cost, subject to a minimum-standards criterion. This is not a simple step, because it ordinarily involves an extremely elaborate analysis to determine the expectation or expected return from the project over an extended period of time for many alternative designs. In general, the discussions that follow will be based on the objective of determining expectation over a long period of operation of a specific project design, rather than the evaluation of the probability of hydrologic events independent of any design.

PROBABILITY OF A SINGLE EVENT

Unfortunately, probability determinations in hydrology cannot be based on deductions from exact knowledge of the mechanism that generates events, as it can in many games of chance. Probability inferences must be based on examination of similar events that have already occurred and on some reasoning as to the manner in which future events might occur in relation to past events.

If events that have occurred are independent of each other and if there is a large number of observations, then reasonably accurate estimates of future probabilities can be made. In general, these estimates are based on the assumption that the frequency with which a specified magnitude will be exceeded in the future is equal to the frequency that it has been exceeded in the past, subject to adjustments for changes in controlling conditions. Methods for making such estimates are described in references 4, 12 and 28.

In making such estimates, difficulties occur primarily when the number of observed events is relatively small in relation to the frequency of future events that is to be estimated. The mathematical nature of the frequency distribution is important in such cases and usually must be deduced from the distribution of the observed events. These events can be erratic and non-representative of future events. Even for sample sizes as large as 100, which must be considered as statistically small, probability estimates can be in error by very large amounts. Consequently, it is ordinarily not wise to accept estimates based only on the observed data, if any additional light can be shed on the problem.

One way of shedding additional light on the problem is to determine a function that is descriptive of the type of phenomena being studied. For example, the logarithmic normal distribution is fairly descriptive of the distribution of rainfall observed at most locations. It is certainly better to use this distribution for a specific study, rather than to base the entire study on data observed for a particular location. The two parameters required for fitting this distribution to the data can be estimated from the data, but even these are uncertain estimates and contribute considerable error to the subsequent frequency estimates. In order to further improve the reliability, such statistics can be estimated more accurately by examining their variation throughtout a large region, rather than basing the estimate only on a single location.

In some cases, much pertinent information is disregarded because of computational and logic difficulties. Often, the largest flow for a year is the only item studied in a frequency analysis, and all other data during the year are ignored. It is expected that stochastic processes discussed below will provide means for extracting and using this additional pertinent information in the record.

After all possible information has been taken into account, there is still considerable uncertainty as to the exact nature of the distribution that characterizes all future events. The degree of this uncertainty can be estimated to some extent by statistical processes. For example, the standard error of an estimated mean can be computed, and a frequency distribution of the errors that can occur in estimating a mean value can be described. The same thing is true of other statistics, such as the standard deviation and skew coefficient. The estimates of these error distributions can be made only under simplifying assumptions relative to the basic frequency distribution. Nevertheless, such error estimates can shed considerable light on the reliability of the frequency determinations.

Estimates of reliability can be used by an engineer to assist his judgment, but it is hoped that they can also be used for objective computations that do not involve personal judgment. A very promising approach is through the computation of expected probability, described in reference 3. This consists of considering the likelihood that a statistic can be larger or smaller than the best estimate by specified amounts and weighting the consequences of any contemplated decision in relation to these likelihoods. This is a rather complex conception but is probably fundamental to objective determinations of hydrologic probabilities and their employment in water resources planning. Very little development of this idea has taken place so far.

INDIRECT PROBABILITY DETERMINATIONS

In many cases, it is not feasible or desirable to base probability determinations for a particular type of event directly on historical observations of such events. For example, the probability of flood damage cannot ordinarily be based directly on historical observations, because changes in development of the flood plain, channel improvements, etc., ordinarily cause erratic variations in flood damages. Also, it is desired to determine flood damages under conditions when the area is protected by flood control works, which requires an evaluation of the effects of protective works on damages. It is ordinary practice to construct a damage frequency curve by combining a flood frequency curve with a relationship between flood magnitude and damages, which implies that for a fixed magnitude of flood there is a fixed damage. This is ordinarily not true of agricultural damages, because the damage is dependent on the state of the crops at the time of flooding. To a lesser extent, it is also not true of other damages, because protective works function differently during different floods, and because emergency measures have varying degrees of effectiveness during different floods. Consequently, there is an added degree of uncertainty introduced when making indirect probability determinations.

This added degree of uncertainty can be extremely large in some applications. For example, rainfall-runoff computations ordinarily include such a high degree of variation between different events that a frequency curve of runoff cannot effectively be computed from a frequency curve of rainfall. Usually, the largest source of error is due to the fact that rainfall for the entire contributing area must be estimated from measurements at a few points, which are usually not representative. There are many other factors that contribute toward this uncertainty, and extreme caution should be used in estimating runoff frequency from rainfall frequency.

Practically no work has been done in evaluating the effects of variatiors in the relationship between two events A and B on the frequency curve for event B based on the frequency curve of event A. Where there is not a very high degree of correlation between the two types of events, the indirect probability approach should probably not be used.

COINCIDENT PROBABILITY DETERMINATIONS

One of the more difficult problems in hydrostatistics is the determination of coincident events. It is important, for example, to evaluate the frequency of runoff on the landside of a levee at times when the river stage exceeds various specified values. This is pertinent to the design of interior drainage and pumping facilities. Some reservoirs have a large amount of conservation space compared to flood control space, and it is important to determine the probability that floods will occur at low conservation stage as well as at high conservation stage. Problems of this type can be solved by use of rather elaborate probability procedures. In general, the more stable of the two events is divided into ranges of magnitude, and the probability that the magnitude within that range will prevail at any specified time is first established. Then, for each range, a frequency curve of the other event is established that corresponds to the condition that the first event is within that range. The quantity of interest, which might be the maximum pool stage, is then determined for each value of the frequency curve, based on a mid-range value of the more stable variable. In this manner, a frequency curve of that quantity is established for each range of the more stable variable. The frequencies represented are then weighted in proportion to the probabilities corresponding to the ranges of the more stable variable. In order to be reasonably sure that the extreme values thus determined are reasonable, it might be necessary to interchange the two variables to check alternative possibilities of rare combinations. Even when such analysis is done most carefully, the results must be considered approximate.

In cases where the two events are independent of each other, such a coincident frequency computation can be relatively simple. However, in most cases there is considerable inter-dependence, and the analysis becomes complex and subject to considerable uncertainty.

COMPLEX PROBABILITY PROBLEMS

The computation of probabilities for some hydrologic variables can be extremely complex. For example, the frequency of reservoir stage during the recreation season at a particular reservoir that is affected by a system of diversions and reservoirs upstream can be extremely difficult to establish. The only approach that has been successfully used in such cases is to simulate the operation of the reservoir system through a large number of years and to treat the resulting reservoir stages in the same manner that observed events are used in establishing frequency curves.

APPROACH TO A GENERAL SOLUTION

As can be noted from the above discussions, the ordinary techniques of frequency analysis leave a great deal to be desired. There is considerable uncertainty in many of the direct applications of statistics as described above, and some of these uncertainties are so large as to require an alternative approach such as the application of stochastic hydrology.

The development of computer technology and some advances in stochastic hydrology show promise of greatly improving the techniques of frequency analysis and the reliability of results; even for simple problems as well as for the problems that are difficult to solve by other means. As an example of a simple application, direct construction of a frequency curve of annual maximum flows based on the few values observed in a short record might be replaced by constructing a daily streamflow generation model based on all daily flows, then generating 1000 years of flows and constructing a curve from the 1000 maximum events.

Regardless of the type of problem, a systems analysis type of simulation can be performed that will determine the magnitude of the pertinent quantity based on given magnitudes of variables for which some data are available. These input variables can be generated stochastically in any numbers, and the simulation study performed to obtain a large "sample" of the pertinent variables for which frequency determinations are required. For example, a multi-reservoir system analysis can be made for a 1000-year period, using stochastically generated inputs. Then a frequency curve of any desired parameter, such as maximum outflow for a given reservoir, can easily be constructed, based on 1000 years of hypothetical observations. The reliability of such a curve would, of course, be far less than one based on 1000 years of actual observations. Various methods for stochastically generating hydrologic variables are discussed in several references cited herein.

Stochastic hydrology is still in the very early stages of development, and there is considerable uncertainty as to the actual reliability of the extreme combinations of events generated. Nevertheless, where records are short or the problems are complex, considerable advantage can be gained by application of these techniques at the present stage of development.

The application of stochastic processes to actual hydrologic problems constitutes a great challenge in the field of hydrostatistics. Mathematical processes that have been considered satisfactory for other purposes are no longer adequate, because they contain minor inadequacies that can accumulate to cause gross errors. For example, in multiple regression analysis, a regression equation is developed from a set of data. This equation is then applied to new values of all independent variables in order to predict a "best estimate" of the dependent variable. This procedure ignores new information contained in the new data that bears on the interrelationships among the independent variables. In some stochastic applications, it is absolutely essential to take this additional information into account if valid answers are to be obtained.

Another area in which stochastic processes require new statistical developments is in the field of statistical inference. The reliability of individual statistics such as a mean or standard deviation of sample data can be readily expressed for certain simple assumed distributions of the data, as discussed above. Even the combined effect of uncertainties in a mean and standard deviation for a normal distribution can be evaluated adequately. However, the combined effects of the unreliability of the large number of interrelated statistics that are pertinent to a hydrologic study is almost impossible to evaluate without stochastic generation. Evaluation of such unreliability is essential to the concept of expected probability and to related concepts that should be used in selecting a best plan of development or operation. In general, these concepts relate to the fact that a great range of "parent populations" could have produced the recorded values, and we should consider the consequences that would result if any of the populations were true.

COMPUTATIONAL FEASIBILITY AND EFFICIENCY

The employment of stochastic processes in combination with systems analysis can require tremendous amounts of computation, even for relatively simple hydrologic or water resource systems. In order to determine the frequency or probability or expectation of a variable such as project benefits reliably, it might be necessary to perform operation studies for thousands of years of synthetic input data. When several plans of development must be considered, the amount of computation required can rapidly become prohibitive.

The question then arises as to the minimum length of operation study that is justified in order to produce reliable results. In general, a partial answer can be obtained only be performing a number of short operation studies in order to examine the variation of results, because direct determination of reliability of results from reliability of input quantities is extremely complicated. Accordingly, it is suggested that about 4 periods of about 25 years of operation studies be performed, and that the standard deviation of the pertinent output quantity be computed. The standard error of the mean of these 4 quantities would represent the reliability of an estimate based on 100 years of generated data. It can be reduced in proportion to the square root of the total number of years used in the study. However, it must be kept in mind that this standard error is based on the assumption of perfect knowledge of the parent populations of the input quantities. This limitation is usually quite serious, and it probably is not warranted to carry computations for more than a total duration of 10 to 50 times the data sample length, except for convenience of analyzing results.

CONCLUSIONS

It is of primary importance in the application of statistical procedures to hydrologic problems that they be carried through a complete analysis from which an objective decision can be made, insofar as is possible. For example, rather than to establish an arbitrary probability that can be used as a design standard, the mathematical expectation of the consequences of a particular design should be computed by statistical and probability means. Of various contemplated feasible designs, the one with the most favorable expectation would presumably be selected.

Hydrologic problems are becoming so complex that the direct application of statistics can result in many uncertainties that are difficult or impossible to evaluate. For example, the frequency of runoff cannot ordinarily be obtained by studying the frequency of rainfall and the relationship between rainfall and runoff, because too many variations in the relationship can affect the frequency of runoff. The application of stochastic processes to complicated hydrologic problems offers a general solution to this problem. However, the science of stochastic hydrology is still in its infancy, and a great amount of theoretical research and practical development remains to be done.

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