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EVALUATION OF THE WORTH OF ADDITIONAL DATA[1]

Donald R. Davis and William M. Dvoranchik[2]

ABSTRACT. Inherent in every decision process is a certain amount of uncertainty, which is reduced with information. Perfect knowledge yields no uncertainty for a process, but perfect knowledge for hydrologic and water resource systems would require a highly excessive investment. Therefore, it is the aim of this paper to delineate a procedure that places a value on this uncertainty so that it may be compared to a cost of further investment, which would provide a basis for deciding the time at which the value of additional data does not exceed the cost of that data.

A decision theory approach is employed on a hydrologic problem to formalize the steps in making a decision. Examples are given.

(KEY WORDS decision theory; uncertainty; information; investment; data)

INTRODUCTION

How much information is enough? It seems that the answer almost always seems to be: more than we have. From the practical viewpoint it sometimes appears that research becomes a merry-go-round of proposals and projects, all needing information to get information. It has been observed [Eberhardt, 1970] that investment requires justification, justification is prediction, prediction embodies uncertainty, uncertainty is reduced by information, getting information requires an investment, investment requires justification, justification . . . etc., ad circulum.

In the construction of a bridge over a river we must have protection against peak flows. Too little protection may result in the loss of the bridge; too much protection is a waste of resources. The same type of statement may be made for a flood control project. The question then arises: What about the uncertainty in the peak flow data—do we have enough information to make an intelligent decision about the protection needed? This paper will make a quantitative examination of expected losses due to insufficient information and expected gains due to additional information. Decision Theoretic Analysis will be used.

The decision theoury approach consists of the following steps:

1) Define the decision to be made and the possible alternatives.
2) Select goal (utility) function
   a) define goal(s)
      i) select state variables (arguments of goal function)
      ii) develop stochastic properties of state variables
   b) establish time preference (discount rate)
   c) include risk aversion (can you accept a big loss seeking a big gain?).

[1] Paper No. 71062 of the *Water Resources Bulletin* (Journal of the American Water Resources Association). Discussions are open until February 1, 1972.

[2] Respectively, Research Associate in Systems Engineering and Hydrology and Water Resources, University of Arizona, Tucson, Arizona; and Systems Engineer, Electronic Data Systems, New York.

3) Making the Decision
   a) evaluate present knowledge (calculate the outcomes of the various alternatives and calculate the stochastic properties of these outcomes)
   b) calculate the expected value of the goal function for each alternative
   c) choose alternative to maximize expected value of the goal function
4) Analyzing uncertainty(ies)
   a) determine expected opportunity loss: XOL (due to uncertainty)
   b) evaluate information gathering programs
      i) determine the expected reduction in expected opportunity loss
      ii) determine full cost of obtaining further information

We define the value of additional information as the expected reduction of expected opportunity loss less the full cost of obtaining the information. Comprehensive details of the evaluation of additional information are given in Raiffa and Schlaifer [1960]. The method is Bayesian in nature.

Essentially, information will be considered valuable only if its possession may cause a change of decision or action.

The listing of the decision process is by no means exhaustive or complete; it is presented with the idea of formalizing the thought processes to reach a decision and thus provide a foundation for evaluating the worth of additional information.

THE PROBLEM DEFINED

Our illustrative problem concerns Rillito Creek, a stream near Tucson, Arizona. The decision problem is: the depth of piles for the construction of a bridge.

We shall ascertain the value of getting additional information (next year's) regarding the maximum yearly streamflow.

Since this paper is an overview of thought, a deep analysis will be avoided. For design of the bridge the work of E. M. Laursen [1969], concerning bridge design and scour analysis, will be adjusted for use in the paper and we will use data presented by the United States Army Corps of Engineers at the Tucson public hearings [1967, 1970] concerning the Rillito Creek.

The 500-foot bridge is assumed to be built over the flood dikes and to rest on four piers each containing 25 piles. The cost for the part of the bridge that may be lost in a flood is $150,000. The cost of sinking the piles is $4/foot. The objective is to minimize the cost due to sinking the piles plus the expected cost of replacement, due to loss of the bridge during a flood as a result of scour undercutting the piles. This is the variable cost of the bridge.

Since we are dealing with flood magnitudes, an analysis must be made on the annual peak flows for Rillito Creek to ascertain its statistical properties

The two parameter, log normal distribution, was found to be a satisfactory representation of the frequency distribution of annual peak flows, and a Kolmogorov-Smirnov test on the data did not challenge this hypothesis

Uncertainty in this problem arises from the lack of knowledge of the exact distribution of the peak flows, in this case lack of exact knowledge of the two parameters of the log normal distribution—that is, the mean and the variance of the logs of the peak flows. With exact values of the two parameters an exact probability of bridge failure can be calculated for any depth of piling Thus, the variable cost of the bridge is a function of the depth of piling (h) and the parameters μ and σ^2 of the log normal distribution: $V(h, \mu, \sigma^2)$. Uncertainty is encoded into the problem by assigning a probability distribution function for the values of μ and σ^2. This probability distribution comes naturally in the following manner.

After the data (yearly peak flows) have been transformed logarithmically, estimates of the population mean and variance are obtained from the sample mean m and sample variance s^2, respectively, for a sample of size n. The probability distribution function which encodes the uncertainty about μ and σ^2 is identical to the one used to calculate the joint confidence limits of μ and σ^2. In this case it is the normal chi-square distribution with parameters m, s^2 and n - 1.

We can now calculate the expected variable cost of the bridge, called the Bayes risk.

$$R(h, m, s^2, n-1) = E_{\mu, \sigma^2} V(h, \mu, \sigma^2) \tag{1}$$

The expectation above is taken over the normal-chi square distribution. This represents a "weighted average" of all possible variable costs; the variable cost calculated for each μ and σ^2 weighted by the "probability" that the particular value of μ and σ^2 used are the true ones.

The value of h that we seek is the h that will minimize the Bayes risk. This value, h*, is the Bayes decision rule with respect to the distribution describing the uncertainty:

$$R(h^*, m, s^2, n-1) = \min_h E_{\mu, \sigma^2} V(h, \mu, \sigma^2)$$

To see how good our solution h* is, we will set up a conference with Professor I. M. Clairvoyant. He can tell us the true values of μ and σ^2: μ_T and σ_T^2. Then we can find the h that will give us the minimum variable cost : h_T.

$$V(h_T, \mu_T, \sigma_T^2) = \min_h V(h, \mu_T, \sigma_T^2) \tag{2}$$

Because we used h* instead of h_T we suffered an Opportunity Loss.

$$OL(h^*, \mu_T, \sigma_T) = V(h^*, \mu_T, \sigma_T^2) - V(h_T, \mu_T, \sigma_T^2)$$

This Opportunity Loss is a measure of the value of perfect information to us. It should be the maximum consulting fee we would be willing to pay Professor Clairvoyant.

Tragically enough, Prof. Clairvoyant's crystal ball was fractured during the annual spring demonstrations on campus. Now for each value of μ and σ^2 we can calculate the O.L., but we do not know which ones represent the true situation. Our solution to the problem is to take a weighted average of OL's, each one weighted by the "probability" that it was calculated with the true values of μ and σ^2. This Expected Opportunity Loss is obtained by taking the expectation of the OL with respect to the normal chi square distribution using m, s^2 and n - 1 as parameters.

$$XOL(h^*, m, s^2, n-1) = E_{\mu, \sigma^2} [V(h^*, \mu, \sigma^2) - V(h_T, \mu, \sigma^2)] \tag{3}$$

where h* is the piling depth chosen on the basis of present data and h_T is the piling depth chosen when μ and σ^2 are known.

We now have the expected value of the worth of perfect knowledge. What we really want to know is the value of more sample—of one more year's data. With his other crystal ball Prof. Clairvoyant could have told us the value of next year's maximum flow; we would have then calculated the XOL with next year's data. The reduction in XOL due to next year's data is the Value of the Sample Information; if the VSI is less than the cost of obtaining the sample we might wait and get next year's information before building the bridge.

But Prof. Clairvoyant has removed all his activities from campus, so we can only obtain an expected VSI. This expected value is obtained by taking an average of the VSI's obtained from each possible value of next year's data weighted by the "probability" of obtaining that data. This is done by finding the expectation of next year's expected opportunity loss XXOL,

$$XXOL\,(m, s^2, n) = E_x\,[XOL\,(h_x^*, m_x, s_x^2, n + 1)]$$

where h_x^*, m_x, s_x^2 are calculated with the new observation x. The expectation over x is based on the probability distribution function for x, but again we do not know the values of μ and σ^2 so we take expectations with respect to the normal chi square. This gives us:

$$f(x|m, s^2, n - 1) = \iint f_N(x)\mu, \sigma^2)\, f_{N\chi}2\,(m, s^2, n - 1)\, d\mu d\sigma^2$$

$$f(x|m, s^2, n - 1) = \frac{n^{1/2}}{(n + 1)^{1/2}\pi^{1/2}}\;\frac{(ns^2)^{(n-1)/2}}{[(n + 1)\,s_x^2]^{(n/2)}}\;\frac{\Gamma(n/2)}{\Gamma(n - 1)/2} \qquad (4)$$

The expected value of the sample information is then:

$$EVSI = XOL - XXOL$$

This is our measure of the worth of one more year's data.

PROGRAMMING METHODOLOGY

Given the preceding theoretical concepts, it was necessary to employ an electronic data processing unit to achieve our results. A computer program was written in Fortran II and IV language for use on the CDC 6400 computer.

The main components of this program are:

1) Search routine for minimum. This was accomplished using a "Golden Section" iterative process [Wilde and Beightler, 1967].

2) One-dimensional integration. Simpson's rule was employed because of programming ease and will be used to judge the error for a more sophisticated integration routine at a later date.

3) Two-dimensional integration. A combination of two one-dimensional Simpson's rules was used, which has the same results as a two-dimensional grid integration scheme. The function being integrated is the normal distribution function multiplied by the chi-square distribution function, where the two random variables are μ and σ^2, the population mean and variance.

4) Objective function. This was described earlier in the paper. It is the function to be evaluated in every calculation to yield our variable costs.

PROGRAM FLOW

The program flow is given in Figure 1. Computational details are given by Dvoranchik [1971]. Yearly peak flows are fed into the computer and an historical mean and variance are computed. A Gamma function of (n - 1)/2 is computed and these three variables are fed to the double integration routine.

Evaluation of Bayes risk is accomplished using the "Golden Section" search over the pier depth. The probability of bridge failure is derived from a statistical error function routine

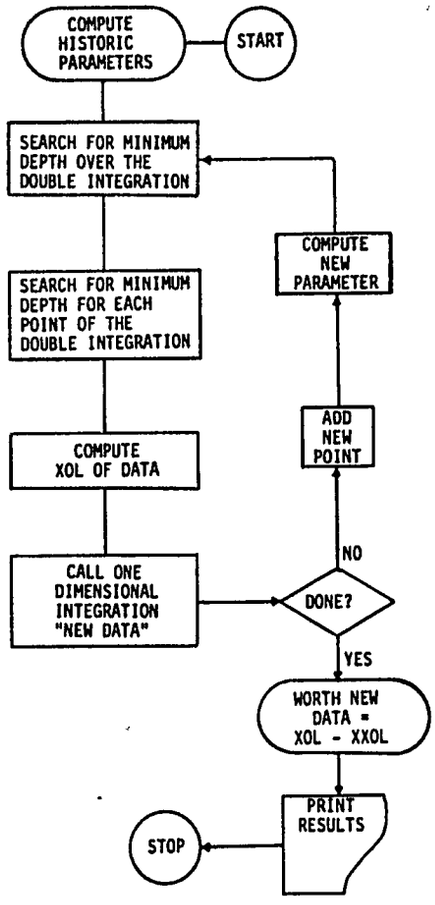

Fig. 1. Computer program.

library package using an appropriate transformation that yields a cumulative normal distribution

To accomplish this, pier depth is transformed into peak flow; the logarithm is taken and then the probability of failure in one year is obtained from the error function The probability of failure at least once in twenty-five years is then calculated and these are fed to the double integration routine to yield a Bayes risk for that pier depth.

The "Golden Section" search is continued until a minimum is found, h^*, and its associated cost $V(h^*, \mu, \sigma^2)$ These are saved for future use in the program

Now, another "Golden Section" search is used to find a minimum, h_T, for each choice of μ and σ^2 in the double integration that minimizes $V(h, \mu, \sigma^2)$.

Employing the relationship stated earlier in the paper, we get an Expected Opportunity Loss (XOL) for the original data. Then we add a new data point and do the entire process again. This is accomplished using the one-dimensional Simpson's Rule with the normal-chi-square-with-concomitant-uncertainty-distribution as the function to be evaluated.

This integration yields the Expected Expected Opportunity Loss (XXOL) for an additional data point. The difference between the XOL of the historical data and the XXOL of the additional data yields the worth of one additional data point.

ERROR LEVELS AND LIMITS OF INTEGRATION

Several choices of levels and limits had to be made and we had to decide on the trade-off between increased accuracy and expenditure on computer time. The following are our selections:

1) Simpson's rule integrations—When two iterations were within 10 percent of each other, the routine was stopped. If a choice of one percent is used, the change in accuracy is less than one percent but the computer time is increased more than tenfold.

The integration limits were set at $Ns^2/30$ to Ns^2 for the chi-square with 9 degrees of freedom, and $m \pm 3s$ for the normal distribution. Additional runs prompt one to infer that increasing the width of these limits is not worth the computer time expended for the increased accuracy.

The one-dimensional Simpson's rule uses limits of $m \pm 4s$ for the range of "new" possible data points, which is better than 99 percent of the area of the normal-chi-square-with-concomitant-uncertainty distribution.

2) "Golden Section"—For our objective function for the bridge design, we chose a relative error of $10 in evaluated difference between the endpoints of the intervals as sufficient accuracy, since the values were only in the 1000's of dollars

This level is fairly insensitive with respect to time. A change to $5 or $20 resulted in less than 40 seconds change in total time, but sufficient accuracy was gotten at $10.

Further computer time was saved by breaking the integration over the chi-square distribution into two segments with limits of $ns^2/30$ to $ns^2/(n - 3)$ and $ns^2/(n - 3)$ to ns^2. This cut down the double integration time by 50 percent.

This basic procedure is also employed for the worth of data study for flood control (to be reported elsewhere) The only changes that are made deal with the probability of the flood are the objective function being evaluated.

RESULTS AND CONCLUSIONS

Table 1 shows results which were calculated with data from Rillito Creek for periods of 5 to 40 years starting in 1920. Table 2 shows results based on 5 years data for several 5-year periods Table 3 shows the effect of partially reducing uncertainty by assuming the mean or variance to be exactly its unbiased estimate Figure 2 shows how the Bayes risk varies with depth.

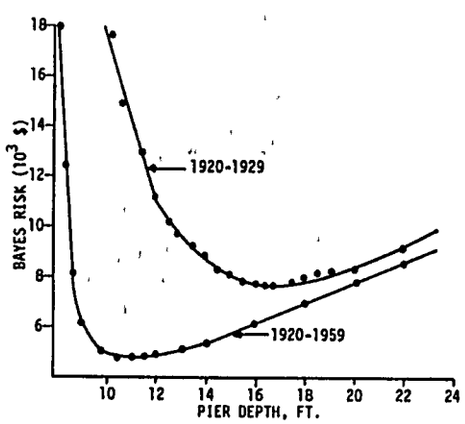

Fig. 2. Bayes risk versus pier depth for design based on 10 and 40 years of data (annual peak flows on Rillito Creek, Tucson, Ariz.).

The results in Table 1 show that the design depth of the piers drops as more data are accumulated. The Bayes risk, XOL and the value of additional data (XXOL-XOL) also drop. The design results for 40 years data impl; a return period of 50,000 years. The physical realizability of peak flows with such return periods is not of concern here, such large return periods arise only because the focus is on the decision to be made with the aid of the data. With less data the implied return periods are orders of magnitude higher. Examination of Table 2 shows the pier depths based on 5 years data are not below the depth based on 40 years data. The results shown in Table 3 indicate that the reduction in XOL occasioned by the knowledge of the population mean and variance separately do not sum to the XOL caused by the lack of knowledge on both parameters

Design modifications other than those discussed here are easily handled by this method; the objective is to choose the design with the lowest Bayes risk. The value of additional information may be expected to change as the design parameters change. The computer program took from 74-181 seconds to run, making the analysis very inexpensive at this accuracy level.

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TABLE 1. Bridge Design Results

	1920-1924	1920-1929	1920-1939	1920-1959
Years	5	10	20	40
$\bar{X}$*	3.7014	3.6670	3.6943	3.6840
S^2*	.0977	.1314	.0890	.0977
Min. Bayes risk, $	12045	7845	5059	4680
At pier depth, ft.	21.2	16.5	11.7	11.0
XOL, $	5,698	2,248	702	331
XOL-XXOL, $	905	246	38	9
Computer time, sec.	181	114	89	74

*$\bar{X}$ and S^2, in this and following tables, are based on the logarithm of the annual peak flow in c.f.s.

TABLE 2. Bridge Design Based on 5 Years Data

	1920-1924	1925-1929	1930-1934	1935-1939	1940-1944	1945-1949	1950-1954
$\bar{X}$	3.7014	3.6326	3.6996	3.7438	3.7037	3.4910	3.7581
S^2	.0997	.1606	.0208	.0716	.1062	.1464	.0822
Min. Bayes risk, $	12405	15327	5766	10322	12481	13575	11164
At pier depth, ft.	21.2	26.2	11.7	18.8	21.6	22.8	20.0
XOL, $	5698	6368	2452	5286	5710	5926	5479

TABLE 3. The Value of Partially Reducing Uncertainty on State Variables in the Bridge Design

	1920-1929	1920-1929	1920-1929	1920-1924	1920-1924	1920-1924
Certain parameters	μ	σ^2	none		σ^2	none
$\bar{X}$	3.6670	3.6670	3.6670	3.7014	3.7014	3.7014
S^2	.1314	.1314	.1314	.0997	.0997	.0997
Min. Bayes risk, $	7527	13287	7845	11459	13500	12045
At pier depth, ft.	16.0	13.0	16.5	20.3	13.2	21.2
XOL, $	1946	1214	2248	5493	1902	5698
Reduction in XOL, $	302	1034		205	3796	

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