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14. ABSTRACT
The value of streamflow data for project design is related to benefits forgone because of insufficient streamflow data. Stochastic simulation of a long-term hypothetical record for a sample station is used to determine a reservoir design based on full (hypothetical) information. Shorter segments of the long-term trace are then used for design under the same criteria in order to compute benefits forgone as a result of lack of full information. For the station used in this study, a low mean flow, high variability station, the marginal value of stremflow data approaches the marginal cost at some time beyond the length on hundred years. The manner in which the value of streamflow data for project design can be evaluated is illustrated.

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water yield, water resources, reservoir design, stochastic hydrology, cost-benefit analysis

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WORTH OF STREAMFLOW DATA FOR PROJECT DESIGN - A CASE STUDY[1]

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INTRODUCTION

Hydraulic structures are designed on the basis of hydrologic and economic data. The cost of data upon which the designs for the structures are based can be determined, but benefits resulting from the data are at best imputed as equal to or greater than the cost of the data. The marginal costs of hydrologic data are approximately constant over time, disregarding general economic inflation or depression. The information content of each added year of data, defined as the reciprocal of the variance of the estimate of the mean for the data, generally is constant over time. However, the worth per unit of information decreases with time. As the worth of information decreases, there may be a point at which the marginal cost and worth of information are equal for a given data set.

In order to design a hydrologic data gathering system properly, the relative worth of alternative types of data must be assessed. A major type of hydrologic data is data on streamflow. The worth of any type of data must be measured in terms of its ultimate uses. Surface streamflow data have two major uses. One use is to provide general regional information. This type of data has transfer value. It represents "natural"

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[1] For presentation at the 49th Annual Meeting of the American Geophysical Union, Washington, D.C., 8 April 1968.

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conditions and may be used in combination with similar data at other sites to gain a regional description of the streamflow of an area. A second use is for project operation and design purposes. Data may be obtained for operations or flood warning, or a surface water streamflow gage may be maintained at a potential reservoir site in order to gain information on which to base the design of a water resource project. Usually such a gage maintained for project design has two measures of worth, for although its primary worth may relate to its project design purpose, if it measures a "natural" basin, its inherent information has transfer value until such time as the dam is built and water is stored in the reservoir.

A measure of the worth of data used for project design may be assessed by measuring the worth of net benefits foregone as a result of the lack of data. If a "true" optimal design and the associated costs and benefits for a given project are known, the change in worth as a result of a sub-optimal design based on a sample of data can be measured in terms of the net benefits foregone, either through underdesign or overdesign.

Unreliability in the ultimate design results from errors in data. Errors in data result from both measurement errors and sampling errors. Measuring errors may be reduced by expending more resources in terms of equipment and manpower so as to obtain more accurate or more frequent measurements of flow. The relative importance of an established streamflow gaging station determines both the accuracy required and the maximum feasible cost for obtaining that level of accuracy for the record.

Sampling error is a more important factor in ultimate reservoir design than is error in streamflow measurement and is usually overriding. Any set of data collected over time at a site provides an estimate of what may occur in the future at that site. The longer the record, the better the estimate. The deviation of this estimate of the future from what will actually occur during a period of interest, say project economic life, is a result of sampling error. The purpose of the present study is to assess this effect of sampling error on the worth of data used for ultimate reservoir design. The pilot study examines the contemplated methodology as applied in a limited manner to one location for design of a multipurpose reservoir for water supply and low flow regulation, with flood control and minimum pool fixed.

DESCRIPTION OF PROCEDURES USED

In order to assess the effect of sampling errors in streamflow data on reservoir design, several factors must be considered. First, a "true" optimum design must be known, so that departures from this design can be measured. Second, the variability of the departures from the true design should depend upon the length of record used for design purposes and the statistical properties of the streamflow for the basin to which the design is applied.

For this pilot study the streamflow record for Arroyo Seco near Soledad, California, was chosen. The measured record of flow was used to establish statistics describing the historical record(1). A 500-year base "record" then was simulated with statistical properties similar to the measured record(2). The 500-year record was used to determine an optimum design for a simplified multipurpose reservoir(3) for both a "high" and a "low" yield at the site, and these designs were treated as true optimal designs for the purpose of comparison in this study. In order to impart realism to the study, seasonal variation of water demand was used, seasonal flood space and constant minimum pool were provided, evaporation was computed, and the reservoir was located so that 20 percent of the runoff above the control point occurs downstream from the reservoir.

An optimum design is a function of cost and benefit functions as well as the hydrologic data used for design. A cost function for construction and maintenance was used (Figure 1) which was based on an average of a group of cost curves for the Delaware River Basin(4).

In order to simplify the pilot study, operation criteria for flood control were held constant. Incidental benefits for flood control were neglected, thus keeping flood control benefits constant. A flood control pool of 50,000 acre-feet was estimated from the historical record. The estimate was based on the flood volumes for various durations, exceeded on the average once per hundred years, and a constant draft at bankfull capacity. The flood storage chosen was based upon the most critical flood duration.

Conservation storage, on the other hand, was optimized with a criterion based upon the percentages of deficits from target flows on a yearly basis. Thus a conservation pool designed for a "50 percent yield" would have a set of target flows which, when summed together, would equal 50 percent of the long term mean annual yield for the basin. Target flows are flows required at a downstream demand point either for water supply or low-flow regulation, or for a combination of both.

The number and amounts of shortages that can be tolerated in the operation of a water resources project depend on the type and nature of use. Large shortages are far more serious in their economic effect than are small shortages, and the economic impact of a shortage under project conditions consequently varies with some power (greater than one) of the percentage shortage. The shortage index used in this study is a function of the square of the annual shortage and is considered to be a practical type of index for ordinary planning purposes. This implies that shortages of 40 percent are 4 times as serious as shortages of 20 percent and that a shortage of 60 percent would be 9 times as costly as a shortage of 20 percent. Use of such a relationship permits the summarizing of all shortages expected within the economic life of a system into a single index convenient for planning purposes. While an actual loss function can differ in mathematical form, it should be possible to select a quadratic function that closely approximates the actual function.

The design assumed to be optimum for the purpose of deriving criteria in this study is represented by a shortage index of 0.25, which is defined as the expected sum of the squares of all annual shortages during a 100-year period, if each annual shortage is expressed as a ratio to the annual demand. This would permit, for example, 25 shortages of 10 percent each during 100 years, or about six shortages of 20 percent each, or one shortage of 50 percent(5). The optimum reservoir size is determined by sequential operation studies (successive approximations) using the entire 500 years of flows, until a shortage index of .25 is attained.

A hypothetical function of shortage index vs. benefits was constructed on the basis that the marginal benefits equal the marginal cost for the optimum size of reservoir, which follows from the accepted definition of economic optimality. Benefits were related inversely to the shortage index. Thus, the rate of change of benefits with reservoir size is computed equal to the rate of change of cost with reservoir size at the optimum size. This rate of change is obtained directly from the typical reservoir cost curve (Figure 1). The rate of change of shortage index with reservoir size is obtained by computing the shortage index for various reservoir sizes (by making sequential operation studies) based on the entire 500-year record. Appendix 1 summarizes mathematically the development of hypothetical cost and benefit curves for a reservoir which maintained a 50 percent yield for Arroyo Seco. Cost and benefit relationships are shown on Figure 2.

Once cost and benefit curves were developed and an optimum reservoir was designed, records of various lengths could be chosen arbitrarily from the the 500-year base record and used to design sub-optimal reservoirs. Each sub-optimal design was so constructed as to develop a shortage index of

0.25 for the particular period of record used. The variability of these sub-optimal designs would be assessable in terms of costs and benefits in relation to the true optimum, and net benefits foregone as a result of sampling error could be determined.

Simulated records of selected lengths were obtained by dividing the 500-year base "record" into five 100-year samples, ten 50-year samples, twenty 25-year samples, and fifty 10-year samples. Pertinent statistics for the simulated records are shown in Table 1.

EXAMPLE

To illustrate the procedure, a brief description of the analysis is presented for an arbitrary demand taken as 50 percent of the mean annual flow. On the basis of the 500-year simulated record and the cost-benefit curves shown in Figure 2, the optimum size of conservation pool for 50 percent yield was found by successive approximations to be 71,000 acre-feet, producing a reservoir with total contents of 131,000 acre-feet, when added to the optimum flood pool of 50,000 acre-feet and the dead storage of 10,000 acre-feet. Eighty-five sub-optimal reservoir designs were similarly obtained based on the 10-, 25-, 50-, and 100-year samples as described above. In order to provide a common basis for comparison, operation studies of 10-year records assumed nine repetitions of the flows to obtain 100 years of operation, those of 25-year records three repetitions, and those of 50-year records one repetition. The results are shown in Table 2. Similar results are shown for a demand equal to 70 percent of the mean annual flow. Over 100,000 years of multipurpose operation by computer simulation were required to obtain the table. For each sample, the size of the conservation pool chosen and the net benefits minus cost (B-C) for the chosen design were computed. Considering that each of the samples is equally likely to occur, the average B-C for each record size can be considered as the expected B-C resulting from basing the design on a record of that given length. As expected, B-C generally increases with length of record. The increase in net B-C between two lengths of record is the "worth" of the added increment of record. Dividing by the length of the added increment gives the average worth per year of added record in that increment. For example, designs for 50 percent yield based upon a ten-year record gives an average B-C of $15,100,000, whereas a twenty-five year record gives an average of $17,900,000. The difference is $2,800,000 dollars gained by adding fifteen years of record, or $2,800,000/15 = $187,000 worth per year on the average for the added fifteen years. As is shown in Table 2, this worth declines as the length of record increases. If costs are about $1,500 per year to maintain a streamgaging station, and if the construction of a $20,000,000 project is planned, the break-even point for cost and benefit for a gaging station used for this one design purpose would be well beyond a length of 100 years. Table 2 indicates that for a reservoir designed to deliver a higher yield of 70 percent of the mean annual flow of Arroyo Seco the worth of data increases. If the construction of a $36,000,000 project for 70 percent yield is planned, the worth of data per dollar of construction cost increases by

2 to 10 times in relation to the lower-yield reservoir. These computed worths are minimum worths. If the data have transfer value, the worth of this transfer value must be included in the total worth for the record.

CONCLUSIONS

A procedure for evaluating the worth of streamflow data for project design has been described, and a simplified example shown. The continuation of this study will include evaluation of streamflow synthesis in design improvement, and evaluation of the worth of transferring data from one location to another. The overall results will be summarized in terms of stream regimen characteristics.

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TABLE I

COMPARISON OF LONG-TERM AND SHORT-TERM STATISTICS FOR 5 SELECTED PERIODS

RECORD LENGTH	STARTING YEAR	ANNUAL STATISTICS		RANGE OF MONTHLY STATISTICS			
		MEAN LOG	STD DEV OF LOGS	MEAN LOG		STD DEV OF LOGS	
				MIN.	MAX.	MIN.	MAX.
500	1	1.980	.325	-1.340	1.271	.363	.964
100	1	1.984	.335	-1.268	1.254	.354	.962
	101	1.987	.314	-1.471	1.278	.365	.988
	201	1.956	.353	-1.257	1.241	.385	.979
	301	2.000	.313	-1.272	1.315	.360	.977
	401	1.972	.313	-1.494	1.317	.346	1.031
50	1	1.957	.317	-1.419	1.236	.355	.982
	101	1.994	.308	-1.668	1.311	.353	1.045
	201	1.930	.340	-1.148	1.212	.348	.932
	301	2.010	.346	-1.242	1.356	.368	.966
	401	1.978	.312	-1.666	1.349	.327	1.066
25	1	1.979	.338	-1.274	1.272	.325	.949
	101	1.976	.371	-1.296	1.322	.369	1.054
	201	1.901	.320	-1.339	1.147	.361	1.035
	301	2.026	.336	-1.571	1.387	.266	1.046
	401	2.054	.359	-1.802	1.437	.285	1.077
10	1	1.838	.327	-1.246	1.207	.212	.970
	101	2.105	.427	-1.085	1.494	.399	1.061
	201	1.914	.333	-1.688	1.279	.382	1.079
	301	2.082	.235	-1.389	1.472	.262	1.086
	401	2.158	.389	-1.964	1.666	.258	1.157

NOTE: All values are in terms of logarithm of storage in thousands of acre-feet.

TABLE 2

COMPUTATION OF AVERAGE WORTH

DEMAND[1]	LENGTH OF RECORD	NUMBER OF RECORDS	RANGE OF STORAGES MINIMUM *thousand*	RANGE OF STORAGES MAXIMUM *acre-feet*	AVERAGE B-C *Million $*	DIFFERENCE B-C *Million $*	DIFFERENCE LENGTH *Years*	AVERAGE WORTH PER YEAR *Dollars*
50	10	50	76.5	202.0	15.1	2.8	15	187,000
	25	20	94.4	191.4	17.9	.7	25	28,000
	50	10	97.5	182.8	18.6	.9	50	18,000
	100	5	109.0	171.5	19.5	1.0	400	2,500
	500	1	--	131.0	20.5			
70	10	50	90.8	(2)	17.1	10.6	15	707,000
	25	20	148.3	349.4	27.7	5.1	25	204,000
	50	10	182.5	396.6	32.8	2.3	50	46,000
	100	5	213.0	368.0	35.1	1.6	400	4,000
	500	1	--	277.0	36.7			

NOTES:

(1) PERCENT OF 500-YEAR AVERAGE FLOW.

(2) THREE 10-YEAR SAMPLES AVERAGED LESS FLOW THAN 70 PERCENT OF THE 500-YEAR AVERAGE. THUS, THE STORAGE REQUIREMENT WOULD BE UNREASONABLY LARGE.

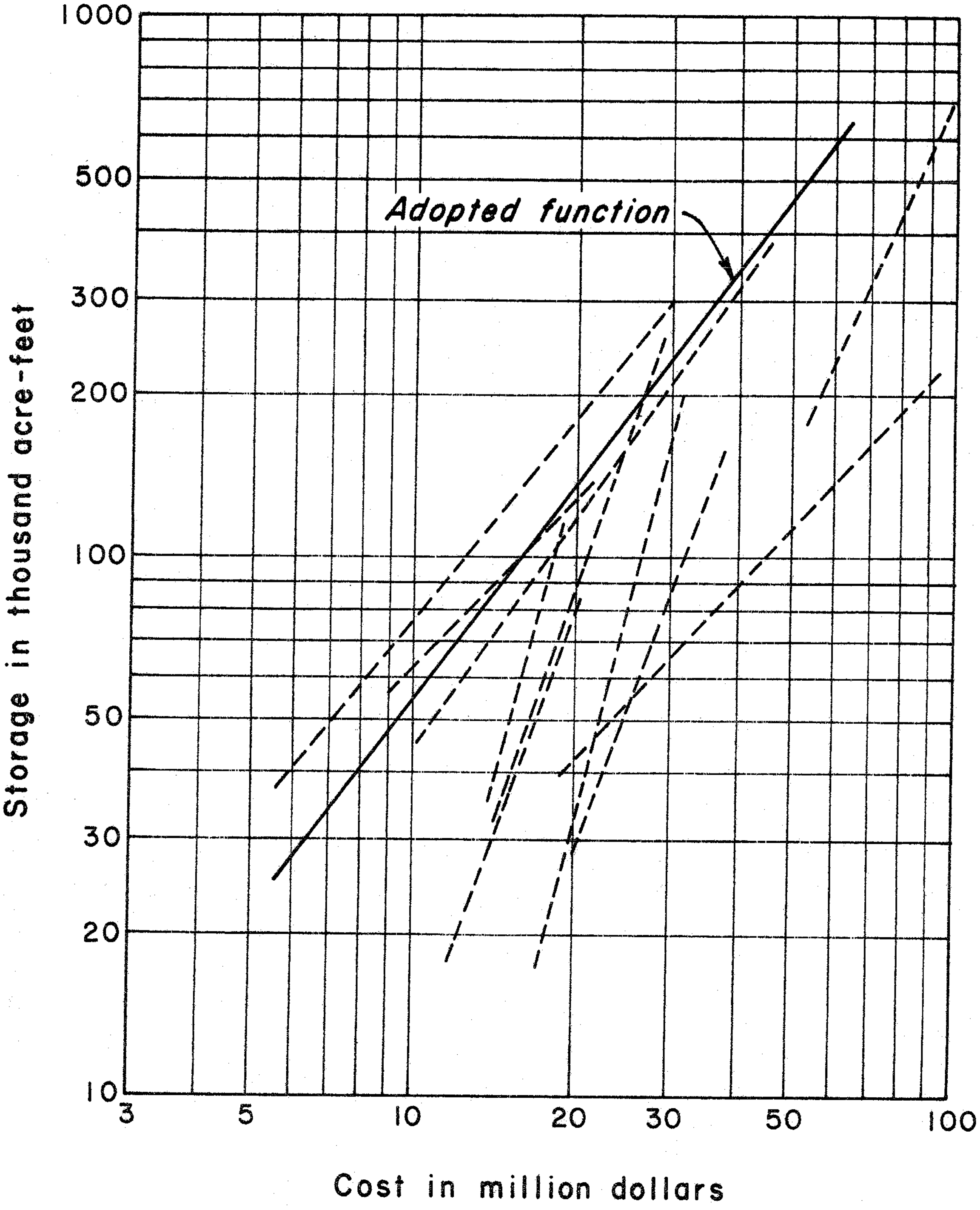

Figure 1

TYPICAL COST CURVES

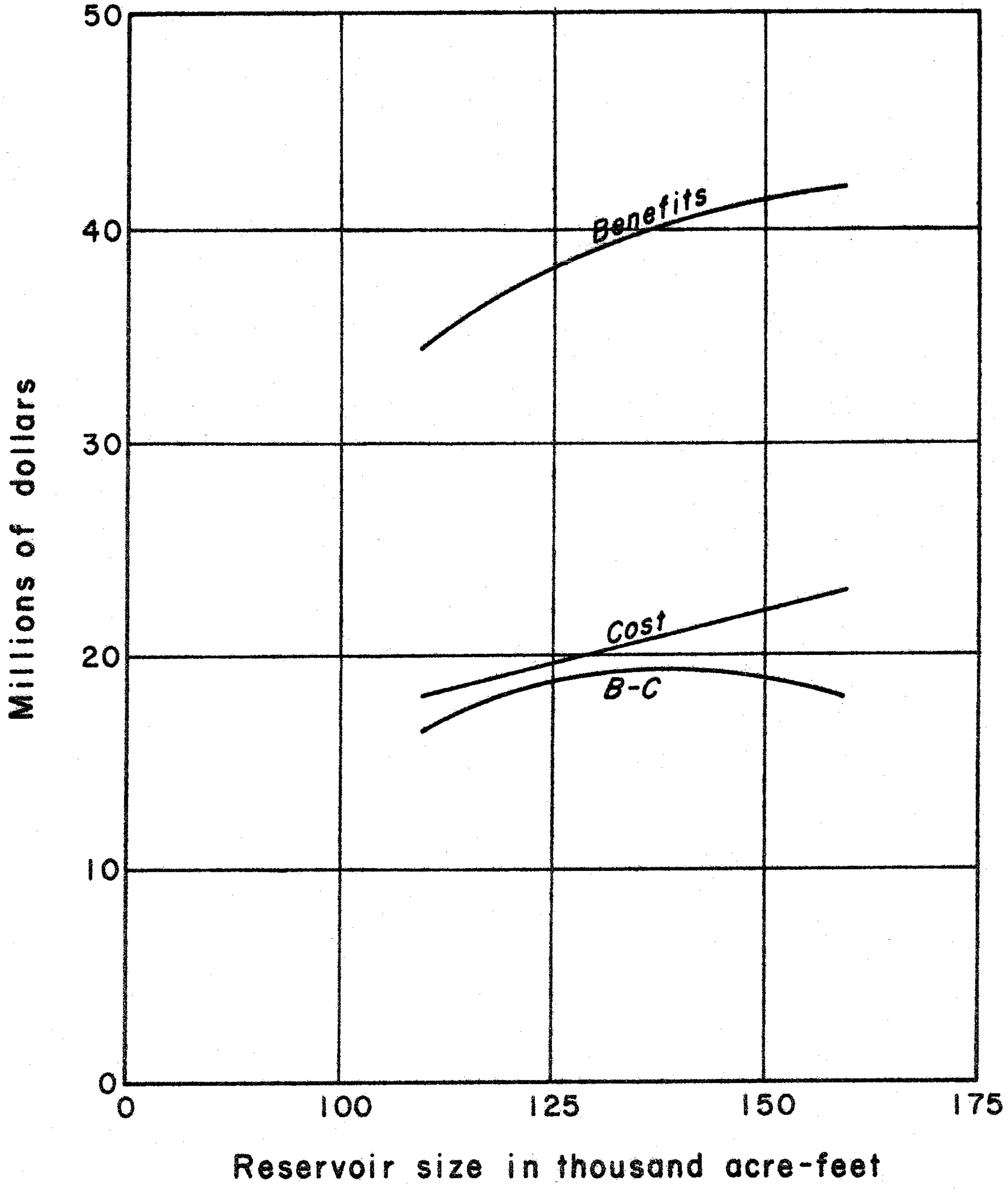

Figure 2

BENEFIT COST FUNCTION

APPENDIX I.--DEVELOPMENT OF COST AND BENEFIT CURVES, ARROYO SECO NEAR SOLEDAD, CALIF., 50 PERCENT YIELD

1. Assume $\left.\frac{dB}{dS}\right|_{opt} = \left.\frac{dC}{dS}\right|_{opt}$

2. Find $C = a_1 \; S^{b_1}$; $\frac{dC}{dS} = a_1 \, b_1 \, S^{b_1-1} = .1207$

   from typical cost curves

3. Find B_{max} which can be based on a worth per acre-foot of water

4. Assume $B_x = B_{max} - KI_x$ $\quad \therefore \frac{dB}{dS} = -K \frac{dI_x}{dS}$

5. $\therefore \left.\frac{dB}{dS}\right|_{opt} = \left.\frac{dC}{dS}\right|_{opt} = .1207 = - K \left.\frac{dI}{dS}\right|_{opt}$

6. Find $I = a_2 \; S^{b_2}$; $\frac{dI}{dS} = a_2 \, b_2 \; S^{b_2 -1}$ (from routing)

7. $\therefore .1207 = -K \left(a_2 \; b_2 \; S_{opt}^{b_2-1} \right)$; $K = - \frac{.1207}{a_2 \, b_2} \; S_{opt}^{1-b_2} = 11.572$

a_1, a_2, b_1, b_2	empirical constants
B	benefits, in millions of dollars
B_{max}	maximum obtainable benefits
B_x	benefits for storage level x
C	cost, in millions of dollars
I	deficit index
K	proportionality constant
S	storage in thousands of acre-feet
opt	indicates the value when evaluated at the optimal point.

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