CHAPTER 13

THE COST OF ADDITIONS TO SAFE YIELD

We now turn to the estimation of the costs of increasing safe yield. We present the results of two alternative approaches, the first based on a general published study of the costs of water supply; the second based on analysis of a number of reservoir projects proposed to several Massachusetts towns over the last 60 years by consulting engineering firms.

A THEORETICAL APPROACH

The problem of determining the cost of additions to safe yield may logically be separated into two subsidiary problems. First, one must determine for a particular stream, subject to a particular climate, the amount of storage required to produce a given (say daily) draft with a given level of assurance. Second, it is necessary to estimate the costs associated with the provision of the required amount of storage.[1]

The first consideration, that of the draft-storage relationship, is clearly bound up with the matter of climatic uncertainty discussed above. The cost of reservoir construction, on the other hand, is conceptually a deterministic function of reservoir size, along with other variables such as terrain and type of construction used. We consider this latter relationship first.

[1] These costs may, in the simplest case, consist of the capital costs of construction of the required dam and the annual Operation-Maintenance-Repair costs required for the new storage facility. More realistically, any decision to provide additional safe yield for a water system will probably also imply costs for conveyance from the new facility to the area of use, and also for construction and operation of treatment facilities. In this study, we concentrate on the capital cost of reservoir construction.

To the extent that other costs are a function basically only of the size of the safe-yield increment, their inclusion then will encourage postponement of construction. If certain costs are time-dependent (in particular, if certain costs can be expected to increase with time) their inclusion will work in the opposite direction by rewarding early construction.

Capital Cost of Increased Storage Volume

The cost functions we present here are based largely on the data provided by Louis Koenig.[2] Koenig presents the results of analysis of the costs of over 1,000 U.S. reservoirs. The cost figures were adjusted to 1962 prices on a regional basis, using the *Engineering News Record* 20-Cities Construction Cost Index.[3] They are presented as median costs ($ per acre foot) for different size classes of reservoirs. For the New England region, data were provided for only four size classes: 10,000; 100,000; 1,000,000; and 10,000,000 ac.ft.

The applicable cost function was obtained by fitting to these points, by eye, on log paper, a straight line. If the total cost function is of the form $C(V) = a \cdot V^{\beta}$ where V is storage in acre feet and β is the scale parameter, then the average cost function is of the form $C(V)/V = aV^{\beta-1}$ or in log-log form, $\log C(V)/V = \log a + (\beta - 1) \log V$ and a and β may be estimated directly from average cost data. The estimates obtained for 1962, New England storage capacity cost parameters were: $a = 19{,}900$ ($\log a = 4.299$) and $\beta = 0.52$.

The results for the scale parameter accord generally with the expectations expressed by Thomas: "The scaling factor, β, usually lies in the range 0.5 to 0.8. It may be as low as 0.3 for some types of storage dams and irrigation canals, and as high as 0.9 for large modern sewage treatment plants with many replicate units."[4]

Sample total costs for various sizes of reservoir are included below in Table 36 to provide the reader with a "feel" for the orders of magnitude involved.

TABLE 36. ILLUSTRATIVE COSTS FOR RESERVOIRS OF DIFFERENT SIZES, NEW ENGLAND, 1962

Storage provided (*ac. ft.*)	Approximate total capital cost ($)	Approximate average cost (*$ per ac. ft.*)
1,000	724,000	724
10,000	2,400,000	240
100,000	7,940,000	80
1,000,000	26,300,000	26
10,000,000	87,100,000	9

[2] Louis Koenig, "Cost of Conventional Water Supply," in *Principles of Desalinization*, K. S. Spiegeler, ed. (New York: Academic Press, 1966), Ch. 11.

[3] See our later comments on this point.

[4] H. A. Thomas, "Capacity Expansion of Public Works," Harvard University, Department of Engineering and Applied Physics, unpublished.

The Draft-Storage Relation

The amount of storage required in a particular situation to assure a given sustained level of draft from a stream at a given probability of failure is given by a draft-storage relation. In general, as the desired draft approaches the mean flow of the stream, the amount of storage increases without limit, but the actual form of the relation will vary across the regions of the country with the variability of streamflow.

We have estimated a draft-storage relation for Massachusetts based on the work of Hazen and Koenig[5] and under the following assumptions:

The required level of assurance is 95 percent (i.e., 5 percent chance of failure);

The average water supply system has available to it a range of stream sources ranging in size from about 10 to about 500 mgd.

The resulting relation, expressed in the form $V = b(D)^x$, where V is again volume and D is draft, is:[6]

$$V = 34.7\,(D)^{1.49} \qquad (13\text{-}1)$$

The Cost of Changing Safe Yield

Now, we combine the results for the cost-of-storage and the storage-draft relations straightforwardly as follows:

$$C(V) = a(V)^{\beta} \text{ (where } V \text{ is storage in acre feet)} \qquad (13\text{-}2)$$

$$V = b(D)^x \text{ (where } D \text{ is dependable draft at about the 95 percent assurance level, in mgd),} \qquad (13\text{-}3)$$

and therefore,

$$C(D) = ab^{\beta}D^{\beta x} \text{ which we rewrite as } C(D) = K(D)^{Y}. \qquad (13\text{-}4)$$

Our estimates give us, then,

$$C(D) = 1.28 \times 10^5 (D)^{0.78}; \qquad (13\text{-}5)$$

[5] See Koenig, "Cost of Conventional Water Supply," and Allen Hazen, "Storage to be Provided in Impounding Reservoirs for Municipal Water Supply," *Transactions of the American Society of Civil Engineers*, LXXVII (1914), 1539–1640. See also Allen Hazen, *American Civil Engineering Practice*, R. W. Abbett, ed., as revised by Richard Hazen (New York: Wiley, 1930).

[6] Actually, this relation was estimated from a scatter of points representing individual draft storage relations for 46 Massachusetts streams of various sizes as indicated above. The R^2 for this regression was 0.69; the standard deviation for x was 0.20; and, with log b estimated as 1.54, its standard deviation was 0.38.

or since $D = \Delta SY$[7]

$$C(\Delta SY) = 1.28 \times 10^5(\Delta SY)^{0.78}, \qquad (13\text{-}6)$$

(1962 construction dollars for Massachusetts in streams with mean daily flows between 30 and 450 mgd). Table 37 gives some sample costs for various safe-yield increments.

TABLE 37. ILLUSTRATIVE SAFE-YIELD COSTS, NEW ENGLAND, 1962

Desired firm draft increment (ΔSY) (in *mgd*)	Estimated total capital cost ($)	Estimated cost (*$ per mgd*)
1	128,000	128,000
10	776,000	77,600
100	4,700,000	47,000
1,000	28,000,000	28,000
10,000	169,000,000	16,900

In the actual planning model we consider the result of considering scaling factors of 0.68 and 0.88 as well as 0.78. This amounts roughly to checking one standard deviation on either side of 0.78, when we treat 0.52 as exact.

AN EMPIRICAL APPROACH

Based on our study of reports prepared by consulting engineers for several Massachusetts cities over the past 60 years, we were able to undertake a direct, empirical estimation of the costs of increases in water system safe yield. In essence this approach involved simply the search of engineering reports for projects for which the reservoir costs per million gallons per day of safe yield were identifiable; the "inflation" of earlier year costs to make them comparable in 1962 dollars; and, then, a regression of the log of unit cost on the log of the safe-yield increment. The sample of projects constructed numbered 20, ranging in size from 0.25 to 12.6 mgd in safe yield. The inflation of the reservoir costs of these projects was carried out using the Bureau of Public Roads Construction Cost Index.[8]

[7] This function is implicitly based on costs of initial development of a stream. The costs of incremental development of existing storage sites may, of course, be the relevant factor for many towns. Our empirical work includes data for projects involving both new development and expansion of existing sites.

[8] From the *Historical Statistics of the United States* and the *Statistical Abstract of the United States, 1966*, Series N-101. This index was used in preference to the familiar *Engineering News Record* index because the latter is weighted with base weights. It thus reflects the construction technology of 1913, the base year, and exaggerates the increase in costs over the past 55 years. The construction industry today is highly capital-intensive relative to 1913, as capital has been substituted for the relatively more expensive factor labor.

Estimating from these data, the function $C(\Delta SY)/\Delta SY = K(\Delta SY)^{y-1}$ in log-log form we obtain the results shown in Table 38.

TABLE 38. REGRESSION RESULTS

$$\log \frac{C(\Delta SY)}{SY} = \underset{(0.0496)}{5.4844} - \underset{(0.0766)}{0.2428} \log (\Delta SY)$$

$$\text{or } C(\Delta SY) = 305{,}000\,(\Delta SY)^{0.76}$$

$r^2 = 0.358$; F-ratio test significant at 1 percent

t = tests for coefficients both significant at 1 percent

95 percent confidence intervals

$\log K = 5.4844 \pm 0.1195$ $(232{,}000 \leq K \leq 402{,}000)$

$\log y - 1 = -0.2428 \pm 0.1846$ $(0.57 \leq y \leq 0.94)$

The most striking result is the excellent agreement between the scale parameter estimate here (0.76) and that found above (0.78).[9]

In our planning model, then, we use as our basic safe-yield cost function the following:

$$C(\Delta SY) = 1.28 \times 10^5 (\Delta SY)^{0.78}; \tag{13-7}$$

and we vary y, the scale factor, using 0.68 and 0.88 as well. K is not varied.

[9] Our empirical estimate of the constant, K (the cost of a 1 mgd project) is a little less than 2½ times greater than the one we found above. One possible explanation of this difference is easy to see. Since our empirical data are drawn from suggested alternatives, only a few of which were ever actually undertaken, whereas Koenig's data represented projects actually chosen, we may expect that our cost data are biased upward relative to his. This will be true so long as a city's choices of actual projects are at least partially based on considerations of unit-cost minimization. To reflect this bias, we have used the K-estimate based on Koenig's work, ignoring the higher value found by the empirical method.