CHAPTER 17

HISTORICAL PROFILES OF FIVE MASSACHUSETTS WATER SUPPLY SYSTEMS: COMPARISON OF ACTUAL AND ATTAINABLE RESULTS

We have suggested that the planning process through which decisions are made concerning the growth of water supply systems in Massachusetts could be improved by explicit inclusion of information about the trade-off between greater system capacity and smaller expected drought losses. The rules of thumb set out earlier appear to offer a way of influencing the decisions of practical men in this direction. At this point it is natural to wonder how the decisions produced historically compare with those which would have been made under our rules of thumb. In this chapter, then, we describe the histories of five Massachusetts water supply systems and compare these histories with the implications of our rules of thumb for system growth.

We present the histories of four systems serving individual communities—Fall River, Fitchburg, Pittsfield, and Worcester[1]—and also that of the Metropolitan District Commission, the regional system serving Boston, its suburbs, and certain other towns.[2] The four communities are all of medium size (serving populations of between about 40 and 190 thousand

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[1] The town of Braintree in which interviews were conducted with various community leaders in our research was not used as a case study for two reasons: (a) it has a town form of government with a Board of Water Commissioners, reducing its comparability with the other communities which are cities, and (b) the series of engineering reports available to trace the history of the water supply system is neither as extensive nor as comprehensive as the series of reports available for the 4 cities studied.

[2] The historical development of the MDC was studied by Donald J. Volk as part of the overall research effort of this project.

people), and they all face mixed domestic, industrial, and commercial demand. The MDC also has mixed demand but is distinguished from the community systems both by its very large size and by its regional authority character.[3] The MDC serves about one third of the population of the entire state—about 1,650,000 people in Boston, its suburbs, and other communities.

SYSTEMS HISTORIES

The history of development for each of the five supply systems is shown diagrammatically in Figures 23 through 27. On these diagrams the estimated safe yield of the system is shown, along with average daily use (both in million gallons per day) on the ordinate. The years from 1900 through 1966 appear on the abscissa. The line representing demand growth is smoothed considerably and may be thought of as a trend line about which daily, annual, and seasonal variations in average daily demand might be

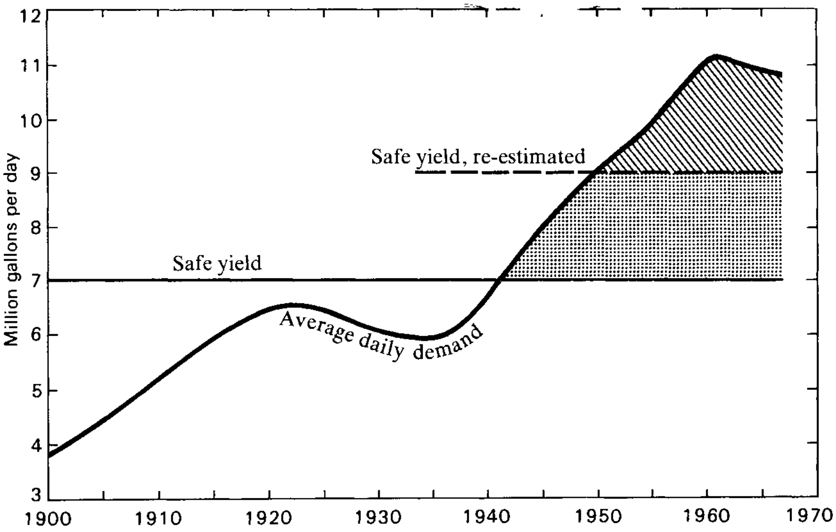

Figure 23. Fall River: average daily demand compared to safe yield.

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[3] All 4 of the cities used as case studies export some water to sections of neighboring communities. Worcester sells water to a section of the town of Auburn; Pittsfield supplies a section of Dalton; the town of Westminster uses one of the Fitchburg reservoirs as its source of water; and Fall River exports water to the town of Tiverton, R.I. In no case, however, is the amount of exported water greater than 3 percent of the larger city's demand.

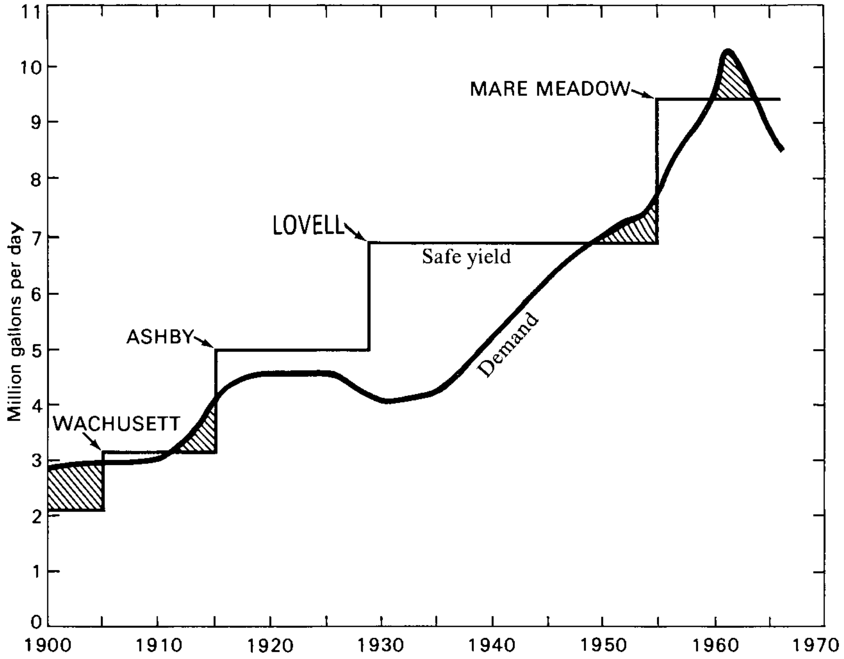

Figure 24. Fitchburg: annual daily demand compared to safe yield.

distributed.[4] Development prior to 1900 is not shown because of the difficulty of acquiring accurate information on safe yield and demand. (The *hatched areas* in Figures 23–27 indicate periods when demand exceeded safe yield.)

The cities of Fitchburg (Figure 24) and Fall River (Figure 23) show highly contrasting patterns of development. In Fitchburg the development profile strongly suggests a tendency to establish excess capacity and thus to lower the long-term risk of water shortage. Fitchburg's development has been unique among the four towns in one respect. The addition of Lovell Reservoir, in 1929, is the only municipal example of a project being constructed when the inadequacy ratio was less than one ($D/Y < 1$). This apparently resulted primarily from the influence of a single elected official.[5]

[4] It is closely related, but not identical to the regression trend lines estimated in Chapter 4.

[5] In an interview in June 1966, J. Andre Provencial, Fitchburg's water superintendent, stated that the mayor in office in 1929 believed in leaving visible evidence of his tenure in the city's strong-mayor form of government and that he was particularly fond of water supply development as opposed to other types of municipal construction.

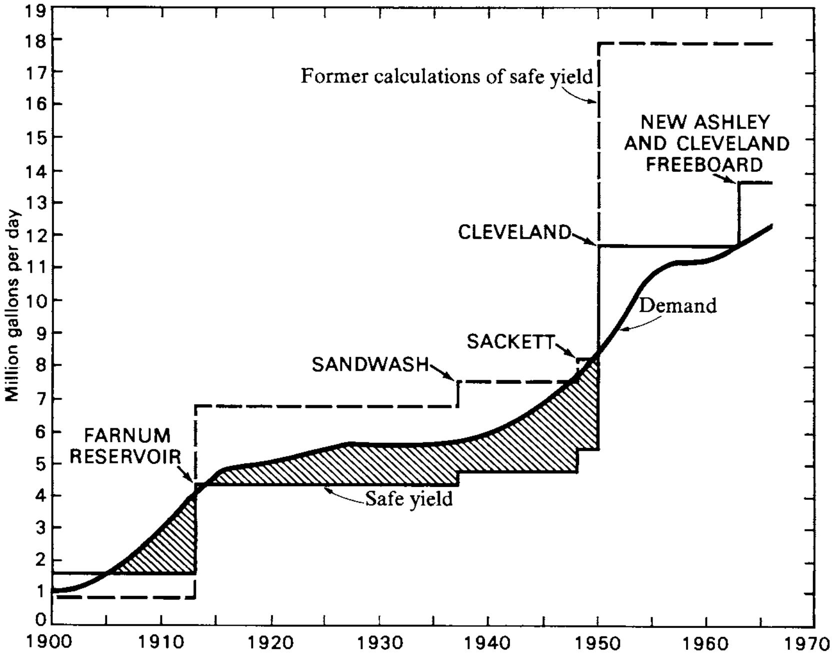

Figure 25. Pittsfield: average daily demand compared to safe yield (*broken lines* indicate prior evaluation of safe yield).

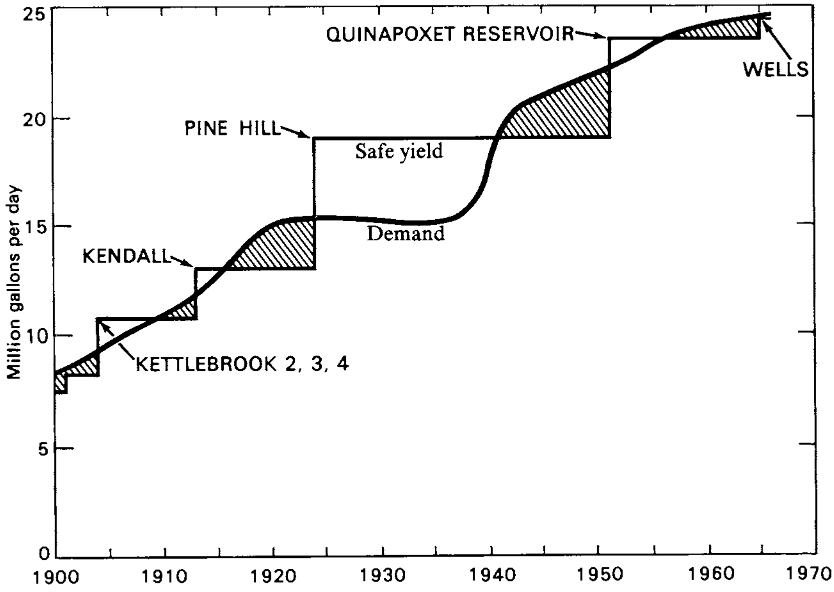

Figure 26. Worcester: average daily demand compared to safe yield.

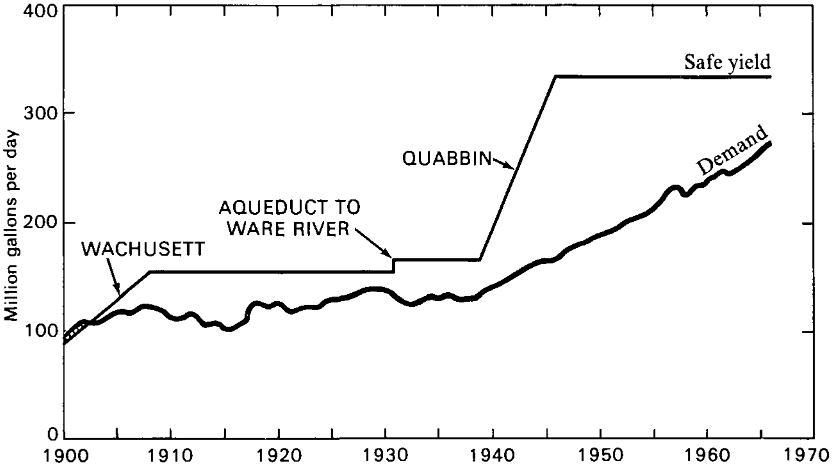

Figure 27. Metropolitan District Commission: average daily demand compared to safe yield.

Fall River provides an example of the early establishment of a natural source of water which fortuitously insured the city against the effects of water shortage for many years. We say fortuitously because when Fall River's source of supply was studied by engineers in 1910 the expected safe yield (as then measured) of the source was 6.5 mgd, not greatly above the demand for that year. In later years the same supply proved to have a safe yield substantially above 6.5 mgd.[6]

Worcester and Pittsfield have displayed mixed patterns of growth. Pittsfield (Figure 25), has had a number of re-evaluations of safe yield which increased the apparent risk of shortage but have not resulted in immediate compensating additions to capacity. Worcester (Figure 26) has added relatively often to its system, but the average size of these additions (as a percentage of the existing system size) has been relatively small. (See Table 47 for comparisons of increment sizes and timing for the four municipal systems.)

One interesting feature of the operating policies of the various towns, which helps to explain the observed differences in growth paths, is the extent to which emergency supplies have been relied on to augment the normal system during dry periods. As we see in Table 48, Worcester has done this very frequently, Fitchburg hardly at all. Pittsfield is second in terms of the number of years in which emergency supplies have been tapped. Even though the Massachusetts Department of Public Health, which has authority to approve sources for such supplies, does not look

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[6] See the comments on predicted and observed shortages in Chapter 7.

TABLE 47. ADDITIONS TO THE CAPACITY OF THE FIVE SAMPLE WATER SUPPLY SYSTEMS IN MASSACHUSETTS, 1900–1966

City	1966 safe yield (in *mgd*)	Capacity added since 1900 (in *mgd*)	Number of additions since 1900	Average size of addition (in *mgd*)	Average size of addition as percentage of existing capacity	Average time between additions (*years*)
Worcester	24.5	19.5	6	3.3	14	11
Pittsfield	14.7	12.1	5	2.4	16	13
Fitchburg	9.4	7.5	4	1.8	19	14
Fall River	9.0	0.0	0	0.0	0	>65
MDC	350.0	260.0	2	130.0	100	35

Source: Unpublished Engineering Reports, available at the Massachusetts Department of Public Health.

TABLE 48. USE OF EMERGENCY WATER SUPPLIES IN 4 MASSACHUSETTS CITIES, 1900–1966

City	Number of years used since 1900	Percentage of years since 1900
Fall River	8	12
Pittsfield	10	15
Fitchburg	4	6
Worcester	18	27

Sources: Unpublished Engineering Reports, available at the Massachusetts Department of Public Health.

with favor on the development of "permanent" emergency supplies, Worcester and Pittsfield have effectively done just that.[7] This development has given these two systems a degree of flexibility not available to the other two.

The MDC, of course, because of its tremendous size cannot plan on having any emergency supplies available during a dry spell; no sufficiently large alternative source exists except for the major rivers, the Connecticut and the Merrimac, which are presently unacceptable. While smaller systems may count on the local recreation pond (or the MDC), the MDC must be its own supplier of last resort. This observation immediately suggests the reason for the differences between the growth path of the

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[7] Worcester has made use of emergency water supply available from the Boston MDC's Wachusett Reservoir, part of which actually lies within the city limits of Worcester. Pittsfield has used emergency supply from a recreational lake, located in the city. Both of these cities have constructed permanent pumping facilities at the sources of their emergency supply.

MDC and those of the other systems. Only two capacity additions have been made to the MDC system since 1900, but both of these increments have been very large. Even more significant, at no time has the ratio of average demand to safe yield been allowed to go above one. That is, the relative system adequacy has consistently been maintained at a high level compared to those levels tolerated by the other systems at different periods in their histories.[8]

This discussion suggests that one important caution should be borne in mind in our examination of the differences between actual and optimal paths of growth: availability of emergency supply sources will probably have a significant effect on the growth path of the system. Our model will not take this into account. When emergency sources become institutionalized by frequent use, or even more definitely by the construction of permanent pumping stations and lines (as in Pittsfield), it hardly seems that they retain their emergency quality. The difference from our point of view is that even these quasi-permanent sources are generally not artificial impoundments but natural lakes and ponds, and the city lucky enough to have such a source at hand may effectively enlarge its system's capacity while avoiding most of the costs we include in the planning model. The fact that such increments cannot be matters of official policy where the Department of Public Works is concerned means also that no planning tools which are to receive official sanction can move into this grey area.

With this problem in mind, we move on to a consideration of the observable differences between the actual growth paths followed by our sample systems, and the path which our rules of thumb suggest would be optimal.

COMPARISON OF ACTUAL AND OPTIMAL PLANNING RESULTS

We need first to translate our historical data on increment size from millions of gallons per day of safe yield to years of demand growth and data on increment timing from calendar time to adequacy ratios. This translation, in turn, involves us in explicit assumptions about the kinds of information the system decision-makers could be expected to use.

Once we translate our data, we do the comparison in two steps. First, we check the average size and timing of increments for agreement with our rules of thumb, for reasonable assumptions about key parameters. (At the

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[8] There are, of course, other important factors which differentiate the MDC. It maintains its own engineering staff and need not rely on infrequent consultations with one or another Boston firm for recommendations and projections. It also has greater powers to take land and greater flexibility in the raising of funds when development has been decided upon.

same time, we compare the towns themselves to see if there are explainable differences in average timing and size choices.) But we should like to be able to say more than just that the towns tend to build bigger or smaller increments earlier or later than would be optimal. For to say that the average increment is 10 percent too big, or that it is added 5 percent too early is not to say much. Whether this is a relatively good, bad, or indifferent performance depends on the implications of the alternatives for total costs over some horizon—and, of course, *as of* some chosen date.

Thus our second approach to the actual/optimal comparison is to take the necessary steps to fit both into the framework of our planning model, noting the differences in total present value of costs under different assumptions about the parameters. This approach requires a second, essentially inverse, set of translations; the size and timing "rules" implied by our model and those discovered in the historical experience of our sample towns must be used to construct vectors $\{T_1, T_2, s_o, s_1, s_2, s_{60}\}$ which can be run through the model to give a total cost result.

TRANSLATING HISTORICAL SIZE AND TIMING DATA

We have historical data on the size of chosen increments in terms of their safe yields, and on the timing of those increments in terms of calendar years. Our discussion of optimal planning has been couched in terms of increments of size τ years added when the adequacy (D/Y ratio) of the system is k. The practical gap between these two is not so great as it might seem, for most system managers are accustomed to discussions of how long an increment will "last" in terms of growing demand. And most also think of adequacy in terms of some relation between their community's water use and their system's safe yield. We think, then, that it is fair to assume that managers acted as if they calculated τ and k, and the central question becomes what information we may reasonably expect them to have had and used at the time of the decision. More particularly, we must decide:

1. What date to accept as "the" date of the decision to build, since no public notice is generally given of the decision *per se*.
2. What information on the level of system adequacy would have been available at that date.
3. On what basis could increment size in safe-yield terms have been translated into a τ figure, i.e., what information on the rate of growth of demand was available.

Our choice of a date for the decision to build had to be chosen from the three times that we were able to tie down for each project from our study of engineering reports and available town and state records. We know the date of the engineering report in which the project was introduced, the date of the loan authorization related to construction, and the date of completion of the project. In these circumstances, it seems clear that the date which best represents the decision to build is that of the loan authorization. In answer to our second question, then, we propose that the ratio of water use to safe yield in the year of the loan authorization be taken to be the adequacy ratio "chosen" for the timing of the addition. The principal problem with this decision is that it is probably reasonable to assume that system managers take account of the various lags between the decision and the time the increment is actually operating. We note below the results of assuming that the managers are able to predict construction lag and demand growth rate perfectly; that is, we calculate the system adequacy ratios for the years of completion of the various projects.

Finally, we adopt as the appropriate measure of demand-growth expected by decision-makers the rate of growth projected by the consulting engineers in the report introducing the project in question.

RESULTS OF TRANSLATING HISTORICAL DATA

The actual calculation of the size and timing values implied by the towns' decisions is straightforward once we have made the assumptions discussed just above. The water-use/safe-yield ratio (WU/SY) for any year needs no explanation, while the size in years, τ, of an increment is calculated from the formula

$$\tau = \frac{1}{\alpha} \ln \left(\frac{s + \Delta s}{s} \right) \qquad (17\text{-}1)$$

where ln denotes the natural log, and s is the existing safe yield before an increment, Δs (s and Δs are measured in flow units, such as millions of gallons per day).

In Table 49 we show the results of these calculations averaged for individual towns and across the entire sample. For timing, we confine ourselves to simple averages of the WU/SY ratios at the time of loan authorization and of construction completion. For size, however, we include both weighted and simple averages, with and without two very large (in terms of τ) projects.[9] Because of the size of our sample, these large observations affect the averages very strongly, and it is best to keep in mind that the very large average increments sizes found with these two projects may not, in fact, be representative. It would, of course, be possible

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[9] The weighted averages are calculated using the safe yields of the several projects as weights.

TABLE 49. ACTUAL AND OPTIMAL TIMING AND SIZE DECISIONS

Timing (PD/SY)	Fitchburg	Pittsfield	Worcester	All
Projects[a]	4	4	4	12
Average WU/SY ratio at time of loan authorization	1.00	1.41	1.12	1.17
Average WU/SY ratio at time of completion of construction	1.12	1.51	1.14	1.25

Optimal PD/SY ratios from model[b] for $\left\{\begin{array}{l} y = 0.78 \\ \rho = 0.05 \end{array}\right.$ and,
for $z = 12$; $PD/SY = 1.12$
for $z = 5.4$; $PD/SY = 1.29$
for $z = 4.3$; $PD/SY = 1.36$

Size: (τ years)	Fitchburg	Pittsfield	Worcester	All
Projects[a]	3	3	2	8
Simple average of all projects	51.2	70.7	27.0	52.5
Weighted average of all projects	56.5	145.0	28.0	70.7
Simple average without two largest	25.6	22.7	27.0	25.1
Weighted average without two largest	25.6	22.8	28.0	26.3

Optimal τ from model for $\left\{\begin{array}{l} y = 0.78 \\ \rho = 0.05 \end{array}\right.$ and,
for $z = 12$; $\tau = 19.4$
for $z = 5.4$; $\tau = 19.4$
for $z = 4.3$; $\tau = 19.8$

Notes:

[a] The number of projects represented in the timing and size calculations reflects the availability of the necessary data on intended safe yield, demand growth projections, etc., within a universe of projects referred to in the system histories.

[b] These rules of thumb were calculated from computer runs for which the initial population was set at 100,000. Subsequently, they were checked from the results of runs for which $N_o = 50{,}000$. In general, optimal sizes (τ) were the same in both circumstances; there was an apparent tendency for the optimal adequacy ratio to be larger (the construction time later) for the smaller town.

to argue that these large projects are simply evidence of overbuilding in public water supply. This seems particularly dangerous here, however, since the rates of growth of demand connected with these two projects, as shown in the engineering reports, were so very low that the town officials might not have taken them completely seriously.[10] We also include in the table the optimal rules of thumb given by our model for three values

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[10] One project, at the projected growth rate of 0.4 percent per year, covered 167 years of demand growth. The other, at 0.3 percent, covered 102.5 years. In neither case did simple extrapolation of existing trends, at the times of the reports and of the loans, suggest that such low rates were realistic.

of the loss-function parameter (z), when the scale factor (y) is 0.78 and the interest rate (ρ) is 0.05. The values of y and ρ have been chosen to reflect the most likely situation; our best empirical estimate of y was about 0.76, and our study of municipal water bonds suggests that an interest rate of 5 percent is a good approximation to the cost of capital in the minds of the planners.

Certainly in terms of the timing of capacity expansion, the evidence in Table 49 is that towns have not been doing badly. If we accept the rules for $z = 5.4$ as our standard, building seems, on the average, to be occurring somewhat early (at adequacy ratio 1.17 instead of 1.29). If, however, we look at the *WU/SY* ratios at the times of project completion, we find this tendency has essentially disappeared. Thus, under the most generous allowance for managers' ability to plan around construction lags, we find them on target in their timing decisions.

The size decisions made by our study towns involve, by any measure, increments larger than the optimal. Here the rule of thumb appears to be independent of the value of z and to call for increments of about 19½ years. Even if we remove the influence of the two very large projects mentioned above, the average of actual decisions is between 25 and 27 years, depending on averaging technique. And, if we include these very large projects, average actual increment size grows to somewhere between 50 and 70 years. Thus, the weighted average project size for all towns and projects is more than three times the optimal size!

None of the towns exhibits a tendency to build smaller than optimal increments, but Pittsfield takes the honors for the largest. The weighted average of Pittsfield projects is 145 years; almost 7½ times optimum size. Worcester projects generally are the smallest, averaging only 27 to 28 years. It is interesting to note that Pittsfield waits longest and builds largest. It is probable that by waiting, overbuilding is encouraged, since the lower adequacy ratios tend to increase average annual shortages and thus to increase public concern about the water system. And public concern seems, in turn, frequently to be translated into highly visible system improvements.

The above comments are, of necessity, essentially qualitative, for in the absence of information on the cost implications of various policies, we have no basis for saying how much better it is to build an optimal increment on time than to build a relatively large increment a bit too early. To make some quantitative judgments about the degree of success of actual system planning, we translate policies into costs, and in order that this be done on a standardized basis, we go back to our planning model with a fixed 60-year horizon and a constraint on the minimum total increment over the horizon.

COSTS OF VARIOUS POLICIES

We now compare the cost implications of observed system expansion policies with those both of our rules of thumb and of the programming model solution itself (without the approximations subsumed in the rules of thumb). We use the actual expansion policies obtained from the town experiences averaged both with and without the two largest projects. Our calculations are done for a city of initial size of 50,000, an initial per capita water use of 100 gpd, and an initial safe yield of 5 mgd.[11]

In Table 50 we show, for each parameter combination, the total present value of costs from the planning model using the vectors implied by the appropriate rule of thumb and the two policies estimated from historical data. In addition, for all but two combinations, we have available a cost benchmark in the form of a programming solution to the planning model. We indicate in the table the percentage differences between the several suboptimal results and this benchmark.

In general our expectations are confirmed by the pattern of results. For given z and α, the costs implied by the town policies including all projects (the largest τ) are significantly larger than those achievable by the programming solution. The largest observed difference between the costs of this policy and those found for the optimal policy is 38 percent; the average difference is about 21.5 percent. The costs implied by the smaller-increment town policy are generally closer to the best attainable mark (average difference = 10.4 percent). And the rules of thumb perform, as we would hope, relatively very well by this test (average difference = 5.4 percent).

If we are willing to accept the evidence of our limited sample that towns are building increments averaging over 50 years of demand growth in size, then we may conclude that the total of costs they are incurring over any particular planning period are significantly above both the best attainable and those attainable using the rules of thumb. These increased total costs will reflect very much larger capital outlays, not balanced by corresponding reduction in expected drought losses. This indicates that the familiar charge of water-supply "overbuilding" may be valid and relatively serious. The present value of the extra cost burden imposed by this overbuilding may be $250,000 to $300,000 for a town with initial population of 50,000 and growth rate of demand of 0.035 over 60 years. We should remember, however, that the managers' best information may include an estimate of a relatively low rate of growth of demand. If such a growth rate in fact prevails, the maximum extra costs, those implied by following the "large

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[11] The actual translation of policy rules into size and timing vectors for the capacity expansion model is basically only a reversal of the technique described above for deriving the rules of thumb in the first place.

TABLE 50. TOTAL PRESENT VALUE OF COSTS IMPLIED BY VARIOUS CAPACITY-EXPANSION POLICIES

		$z = 4.3$			$z = 5.4$			$z = 12.0$		
α		Total present value of costs ($)	Percentage difference from programming solution	Percentage difference from rules of thumb	Total present value of costs ($)	Percentage difference from programming solution	Percentage difference from rules of thumb	Total present value of costs ($)	Percentage difference from programming solution	Percentage difference from rules of thumb
0.003	Programming solution	[a]			[a]			150,600		
	Rule of thumb	128,900	[a]		137,500	[a]		190,800	21.1	
	Small increment policy[b]	130,000	[a]	0.8	137,800	[a]	0.2	205,800	30.0	2.6
	Large increment policy[c]	130,000	[a]	0.8	137,600	[a]	0.1	203,400	28.4	1.4
0.015	Programming solution	312,000			324,000			340,400		
	Rule of thumb	315,900	1.2		[d]	[d]		353,300	3.8	
	Small increment policy	321,100	2.9	1.6	325,000	0.3	[d]	361,900	6.3	2.4
	Large increment policy	347,400	11.4	10.0	350,200	8.1	[d]	373,000	9.6	5.6
0.035	Programming solution	763,900			803,000			860,900		
	Rule of thumb	797,500	4.4		807,100	0.5		871,400	1.2	
	Small increment policy	877,100	14.82	10.0	930,600	15.9	15.3	881,500	2.4	1.2
	Large increment policy	1,053,900	38.0	32.2	1,059,000	31.9	31.2	1,058,900	22.9	21.5

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[a] For two parameter combinations, the programming algorithm proved to be completely unreliable. Apparently the previously discussed zero-increment (s_o) problem was exaggerated by the generally small size of all the increments when α is very small.

[b] "Small-increment policy"—based on $\tau = 26.3$, the weighted average project size determined without considering the two largest projects. (From historical data.)

[c] "Large-increment policy"—based on $\tau = 41.6$, somewhat less than the simple average product size with all projects included. (Historical data.)

[d] For $z = 5.4$, the rule of thumb derived from the solution for $\alpha = 0.035$ did not prove satisfactory for $\alpha = 0.015$. Since for $\alpha = 0.035$, $s_o \neq 0$ while for $\alpha = 0.015$, $\hat{s}_o = 0$ is probably true, we surmise that this is another manifestation of the zero-increment problem.

increment" policy, are significantly lower. For example, the average difference between best and worst costs when $\alpha = 0.015$ is only a little over 8 percent. Thus, if managers expect low growth rates, it may not seem worth their while to exert themselves in the search for better planning rules. This consideration is, of course, quite independent of questions about political constraints, alternative objectives, etc., which we have raised previously.