PART I

WATER SUPPLY AND DEMAND: THE LEVEL OF SYSTEM INADEQUACY

CHAPTER 2

AN INDEX OF WATER SYSTEM INADEQUACY: THE RELATION BETWEEN POTENTIAL DEMAND AND SUPPLY

As we have pointed out, the central variable in our progress from a study of the drought itself to prescription for optimal system expansion is the level of adjustment of a water system to the threat of water shortage. To this level we must attempt to relate losses incurred during the study period; on it will depend our extrapolation from the results of a single event to long-run expected-loss functions; and with it as the choice variable or policy instrument, we shall construct our planning model. It is thus important that we choose as the representation of level of adjustment a variable, or combination of variables, having at least the following useful properties:

We must be able to measure the actual levels of adjustment of systems observed during the drought;

We must be able to relate the level of adjustment directly to probability statements about the likelihood of climatic events of varying levels of severity; and

We must be able to show explicitly how the level of adjustment of a system will vary over time as a function of expansion decisions (and any other choice variables) and as a function of any time-dependent changes assumed to be exogenous.

With these requirements in mind, we have chosen for our index of adjustment level the ratio of potential demand for system deliveries at the existing price to the "safe yield" of the system, the measure of the probabilistic ability of the system to provide water.

Contrast, for example, the ratio of *hourly* demand to system distributional capacity, and that of the *annual* demand to the 95 percent assured flow provided by system storage. Either ratio may be considered a measure of system inadequacy (for the appropriate run), in the sense that systems higher on the scale are less adequate than those lower on it, i.e., they have smaller supply capability relative to projected demand. The decision-maker for the system "chooses" the level of the demand-to-supply ratio for the appropriate run, over the planning horizon, generally by choosing a level of supply. In these circumstances, whether or not shortage occurs—and if it occurs, how serious it is—depends on the outcomes of the events produced by nature, i.e., on the climatic variation.

In the short-run situation, "the" projection of demand may be viewed as the mean (or some other measure) of a distribution of possible levels of demand depending on (we assume) the air temperature at the given hour. The level of supply is *chosen* in the form of the capacity of the distribution system. (This choice will, no doubt, be related to the projection of demand.) Thus, for a chosen demand-to-supply ratio, there will be a relation between the actual air temperature occurring and the level of short-run shortage. Since the actual air temperature occurring is a random variable, it will, in principle, be possible to find the expected shortage for any chosen level of the demand-supply ratio. If we also have information relating economic losses to level of shortage, we will be able to find expected losses for given levels of system adequacy.

Fundamentally, the long-run situation is the same in that our ultimate aim is a function relating levels of system adequacy to the losses we can expect to suffer as a result of climatic variation. Because this situation is the one dealt with in this book, it will be discussed here more fully than the short-run problem. In order to postpone discussion of the conceptual difficulties in defining "supply" in the long run, we shall adopt an approach that is somewhat artificial but will convey the essentials of the problem.

Let us say that a community projects its total annual demand for water as *D* million gallons. Let us, for simplicity, now assume that this level of demand is expected to last into the indefinite future. Let us further suppose that this town has available to it an infinite number of streams of different sizes which it can tap for a run-of-the-river supply. We assume that for each stream, annual streamflow (*SF*) is a random variable and, again for simplicity, we shall assume that it is serially independent and that the flows are all spatially independent as well. The distribution for each stream is essentially the same (as measured, say, by the ratio of a standard deviation to mean), and we shall distinguish between them on the basis of the "5 percent low flow" (*SF**), that level of streamflow than which the actual

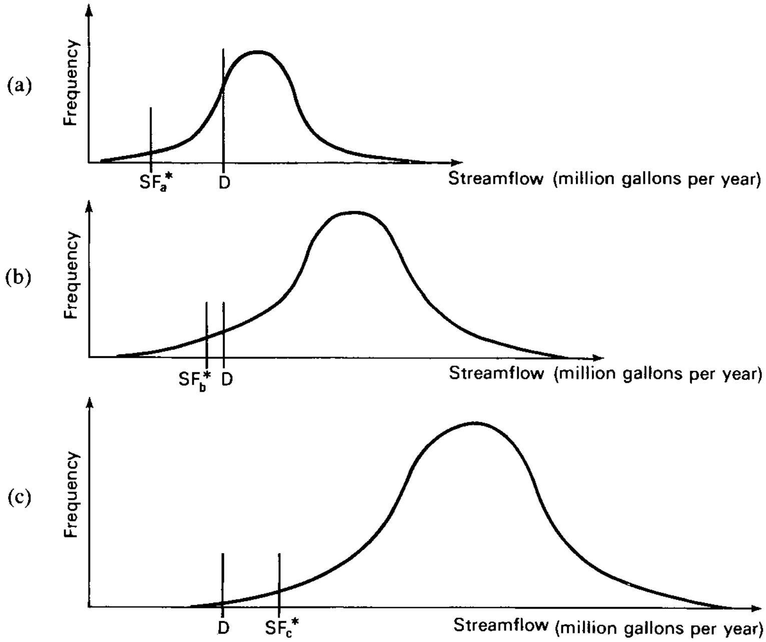

Figure 3. Illustrative supply source choices.

flow will be greater 95 percent of the time. In Figure 3 we have drawn three such streams. In each case, we show the projected demand (D) on the flow axis.

Now, it should be clear that the choice of a particular stream implies both a particular frequency function for shortages, where we define percentage shortage as $(D - SF)/D$ in any particular year, and a particular value for the ratio D/SF^*. We show in Figure 4 frequency distributions for shortages and surpluses corresponding to choice of streams (*a*), (*b*), and (*c*) in Figure 3.

Using these shortage-frequency functions we can find, for any particular stream, the expected annual shortage implied by that choice. Characterizing system inadequacy by the ratio D/SF^*, we can thus construct a relation showing expected annual shortage for each level of inadequacy (for each choice of source). Such a relation is shown in Figure 5. Since we are interested in the economic impact of shortage, we first transform shortages into annual losses through a shortage-loss relationship as illustrated in Figure 6. It seems reasonable to suppose that in such a relation, costs would increase with shortage, though it is not clear whether this increase should be linear or more than or less than proportional. For exposition,

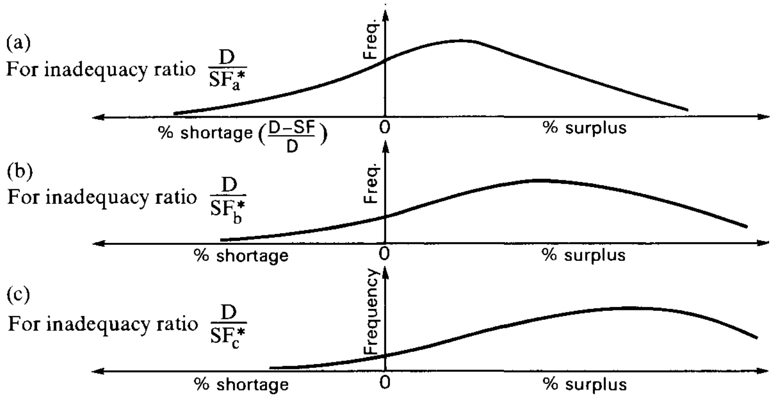

Figure 4. Supply reliability resulting from different choices of source.

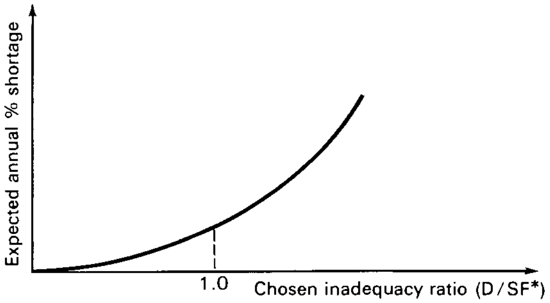

Figure 5. Illustrative expected shortage—system-inadequacy relation.[2]

we assume a more than proportional increase.[3] We are then in a position to derive the cost analog of Figure 5, an expected-loss/system-inadequacy relation. Functions of this type may, then, be used in making choices between various possible levels of system adequacy, as we describe below.

OBSERVED LEVELS OF ADJUSTMENT OF WATER SYSTEMS

Before turning to more careful definitions of the key demand and supply variables in our index of inadequacy, let us pause to examine actual distri-

[2] The claim that we adequately characterize each choice by the expected shortage it will produce is essentially equivalent to stating that the aim of the system is to meet all demand generated at the going price. System surpluses are indistinguishable from a just-adequate supply. Surplus water is of no use to system customers who cannot adjust to quantities greater than their intended demands.

[3] In this static situation (fixed demand into the future) and for illustration, total losses may be used without any problem. When, however, we work with the actual model and data, losses measured at one time are applied to future (different) situations. Then we shall need to express losses in per capita terms.

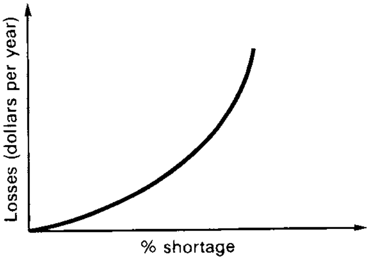

Figure 6. Illustrative loss-shortage relation.

butions of systems on this scale. Such an investigation should help to give us a better "feel" for the index and, in particular, should allow us to judge what range of index values is relevant for the application of our results. In what follows, we discuss such distributions determined both cross-sectionally (for many systems in each of several geographic regions of the United States at one point in time) and over time (for four Massachusetts cities over about 66 years). Since the "demand" estimates involved in all these data are merely point measurements of actual water consumed, we shall refer to the ratios as water-use/safe-yield ratios (WU/SY).

CROSS-SECTIONAL DISTRIBUTIONS OF WATER-USE/SAFE-YIELD RATIOS (WU/SY)

In constructing the distribution of WU/SY ratios, we have relied primarily on data gathered by the U.S. Public Health Service in 1962, just prior to the drought,[4] supplementing this information with data from our study wherever possible.

Because of the fundamental conceptual differences between the measures of capacity for groundwater as opposed to surface-water sources, we first separated the inventoried systems into three groups according to their degree of dependence on surface water.[5] As we have noted previously, our investigation centered on systems depending primarily on surface water.

As a first step, the WU/SY ratios were calculated and plotted for the population supplied by surface water in Massachusetts. Because of the relatively small number of such communities with complete data, gaps

---

[4] U.S. Department of Health, Education, and Welfare, *1963 Inventory of Municipal Water Facilities*, Public Health Service Publication No. 775, rev. (Washington: U.S. Government Printing Office, 1964).

[5] Systems are classified on the basis of the proportion of the "dependable"supply which comes from each source (the safe yield of surface -water supplies or the maximum dependable draft of groundwater supplies). If 80 percent or more is accounted for by surface supplies, the system is classified as surface; if 80 percent or more comes from groundwater supplies, the system is classified as groundwater. In combination systems, both surface and groundwater supplies account for 20–80 percent of the total.

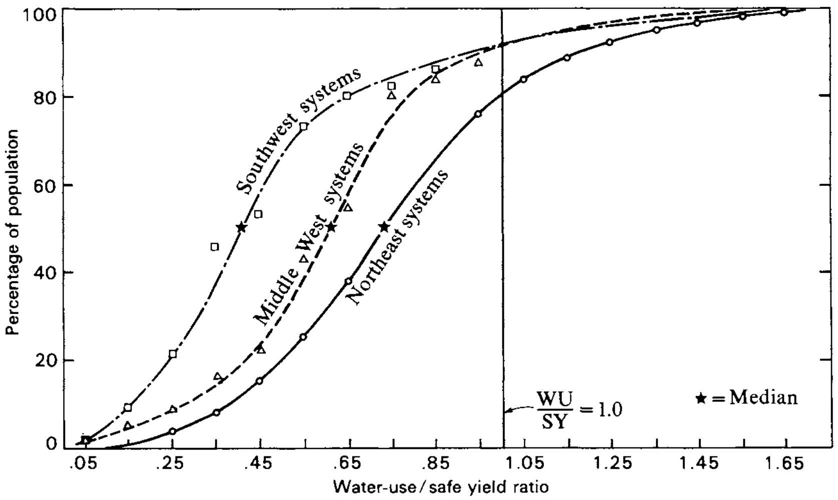

Figure 7. Interregional comparison of the distribution of population over the water-use/safe-yield scale.

appeared in the distribution. It was the existence of these gaps which led us to use the USPHS data for all of the northeastern states.[6]

The data for the Northeast are plotted as a cumulative distribution in Figure 7. In the same figure, we present for contrast similarly defined distributions for two other sections of the United States: the Middle West and the Southwest.[7]

From the distribution for the Northeast we note that the median system ratio is about 0.73. This means that in 1962, half of the population represented was served by systems with safe yields at least 37 percent greater than current water use.[8] About 20 percent of the population was served by systems with safe yields less than use. These people are the ones we would expect to suffer in a repetition of the design drought.[9]

[6] The additional states used were: Maine, New Hampshire, Vermont, Rhode Island, Connecticut, New York, Pennsylvania, New Jersey, and Delaware. Note that differing definitions of safe yield between states and between cities within each state, based on differences in consulting engineering practices, will tend to make the various WU/SY ratios not comparable. We have assumed that this problem is not particularly severe because of the prevalence of safe-yield definitions based either on the 1908–11 drought or on some measure of a "5 percent event."

[7] The Middle West distribution is based on USPHS inventory data for Illinois, Indiana, and Ohio. That for the Southwest is based on data for Texas, Oklahoma, and New Mexico.

[8] For those systems with $SY > WU$, we may write $SY = WU(1 + \alpha)$ and hence $WU/(WU)(1 + \alpha) \leq 0.73$ or $\alpha \geq 0.37$.

[9] "Design drought" is discussed in Chapter 3.

A comparison of the three distributions indicates the dramatic differences between the regions, differences which appear to be related to climate. Both the Middle West distribution and that for the Southwest lie everywhere above that for the Northeast; and the Southwest distribution is almost everywhere above that for the Middle West. This indicates that for any given inadequacy level a greater proportion of the population of the Southwest will be served by systems with at least that much capacity relative to demand (with WU/SY ratios less than or equal to the given level). For example, about 67 percent of the population represented by the Southwest curve is served by systems with WU/SY ratios less than or equal to 0.5, that is, by systems with safe yield at least twice as great as water use. The corresponding figure for the Middle West is 32 percent; for the Northeast, 20 percent. The median system inadequacy level for the Southwest is about 0.41; that for the Middle West, about 0.60.

These measures indicate that levels of system *adequacy* are generally highest in the Southwest and lowest in the Northeast. This corresponds to the interregional differences in the variability of precipitation and streamflow; such variability is greater in the Southwest than in the Middle West and greater in the Middle West than in the Northeast. Thus this measure is clear evidence of the reliance in the West on man-made systems as opposed to the tendency of the East to rely on its more regular rainfall.

We should note that safe yield is, in one sense, no "safer" in the Northeast than in the Southwest. In both areas, events worse than the safe-yield event may be expected about 5 percent of the time.[10] It may be, however, that because of shorter records (along with greater variability) the safe yield estimates available to western water system managers are considered by them to be particularly rough. This greater uncertainty might very well lead to the inclusion of substantial safety factors in system plans.

TIME SERIES DISTRIBUTIONS OF WU/SY RATIOS

Data have been gathered for four Massachusetts communities—Fall River, Fitchburg, Pittsfield, and Worcester—on the changes in water use and safe yield over the period from 1900 to 1966. A detailed analysis of these system histories is presented in Part V. At this point we are, however, interested only in the distribution on the inadequacy scale implied by the

[10] It is possible that in the area of greater variability (as measured, say, by the variance of annual precipitation totals) the physical severity of the 1 or 2 percent event is worse, relative to the safe-yield event. This, however, need not be true.

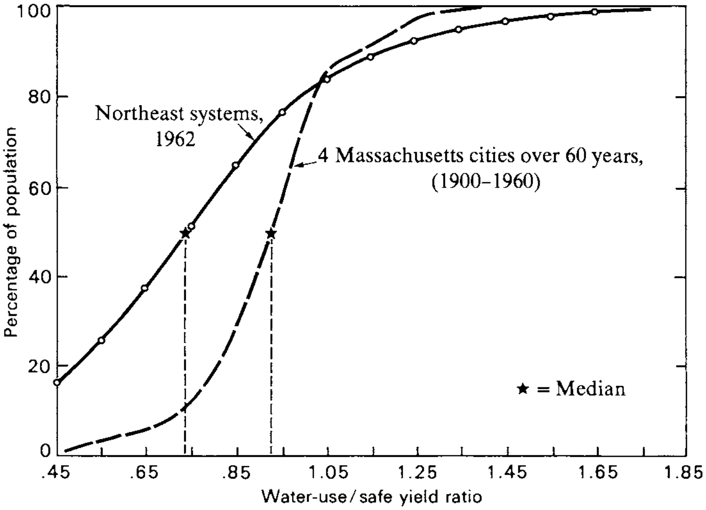

Figure 8. Historical distribution of 1900–1960 populations of 4 Massachusetts cities over water-use/safe-yield scale.

historic experience of these cities. Accordingly, the data are plotted in Figure 8.[11]

In comparison with the cross-sample of Northeast systems in 1962, the time series distribution is more compact and has a higher median adjustment level (the systems tended to be more inadequate). The compactness is probably largely accounted for by our method of construction. It is not clear to what we should attribute the other phenomenon.

This brief study of the observed behavior of water system decision-makers in terms of our inadequacy ratio suggests that a model of drought impact which is satisfactory for systems in the range $0.50 \leq PD/SY \leq 2.00$ will be covering the empirically important cases of chosen inadequacy levels. It is important to note this, particularly since our later evidence on drought impact is drawn from systems in this range, a range we may say includes virtually all systems.

---

[11] The following method was used to construct this distribution. First, WU/SY ratios were calculated for each city and year. Then the median WU/SY values were chosen for each city for 10-year intervals centered on the decennial census years. This median WU/SY ratio was weighted in each case by the city's population for the census year contained in the interval, and the combination of median WU/SY and population weight was considered as a separate system. The total population summed over all the census years and the four cities was taken as the base for calculating the percentage of population served by systems below the various WU/SY ratios.