CHAPTER 3

WATER SUPPLY SYSTEMS AND THE LEVEL OF SUPPLY

Water supply systems are complex networks designed to collect, store, and distribute water. Our concern is with the functions of collection and storage, since these are most important to an understanding of the impact of long-term rainfall shortage.[1]

It is, of course, true that many urban water problems are distributional in nature; that is, while storage may be adequate, the annual, or more often the seasonal, daily, or hourly peak demands exceed the capacity of the pumps and lines that make up the distribution system. The problems raised by these demand patterns are serious, and it may be that drought-related uses such as lawn-sprinkling contribute significantly to the existence of shortages for towns on the border of distributional adequacy. It is, however, our purpose to study the shortages which arise from a lack of water to distribute rather than those resulting from inability to distribute available water in conformance with the pattern of peak demands.

Considered, then, from the point of view of collection and storage, the water supply system planning process is, in outline, a simple one. The planners, in response to actual and anticipated levels of demand for water, seek out and examine available alternative sources of supply.[2] In the genesis

[1] As a consequence of our emphasis on collection and storage aspects of water supply, our discussions of flows (annual, monthly, or daily) will almost invariably refer to average amounts over some particular period (e.g., mean long-term annual streamflow). The reader will be warned whenever it is necessary to discuss peak flows.

[2] The general philosophy of system managers and municipal governments is to meet all demands at the current price structure. The implications of this approach have been discussed by others, e.g., Jack Hirshleifer, James C. DeHaven, and Jerome W. Milliman, *Water Supply: Economics, Technology and Policy* (Chicago: University of Chicago Press, 1960). For the most part we accept this as given.

of the system, these alternatives may be limited by the myopic vision of the planners, and in existing systems further constraints are implied by past decisions. Nevertheless, there is almost always a choice of size and timing of development, and frequently of source as well (i.e., a choice between ground or surface water; location, size, and quality of stream). And, almost always, the size and timing problem is one of balancing the costs of expansion (usually under conditions of falling unit costs) against some notion of the costs of shortages to be expected in the absence of expansion. (See the discussion and planning model presented in Part IV below.)

Given these fundamental influences, then, the growth of a typical water system, when viewed in historical perspective, might take the form shown in Figure 9. Demand, as the product of innumerable individual decisions, varies nearly continuously and generally upwards, reflecting both a growing urban population and increases in per capita water use. (See Chapter 4.) On the other hand, the effect of the existence of economies of scale is to cause supply to move in large, discrete steps. Hence, the characteristic pattern of system growth involves the periodic introduction of "overcapacity," and the eventual elimination of that cushion through steady

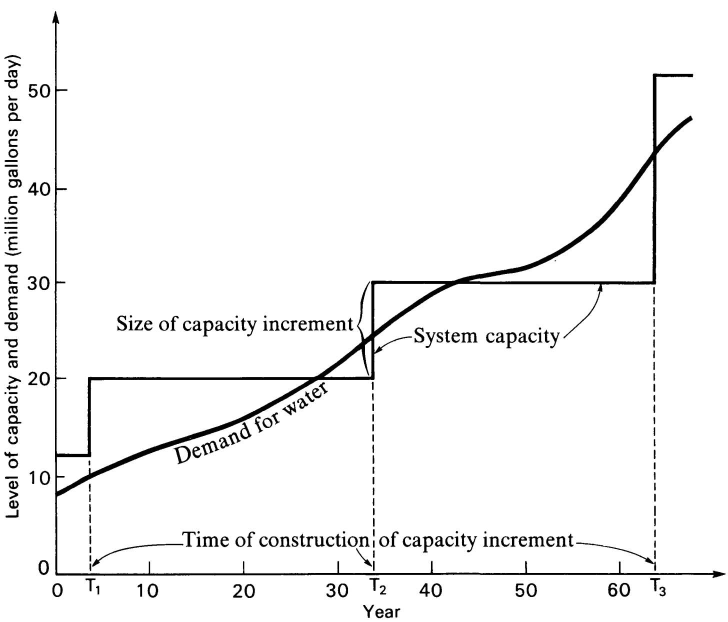

Figure 9. Illustrative trace of water use and system capacity over time.

demand growth, the latter in turn leading sooner or later to a further discrete increment to supply.[3]

Now, it is intuitively reasonable to suppose that the impact of any given climatic event (e.g., any given level of precipitation shortfall) will be different for systems with different relations between supply and demand. Thus, a system which has just completed a large addition to its capacity should probably be better able to meet the demands of its customers than one which has allowed demand growth to outrun available supply. This notion was already outlined schematically in Figures 3–5.

CAPACITY: THE SAFE YIELD OF SURFACE-WATER SOURCES

The basic supply capacity of a water system (as opposed to its distributional capacity) is a product of its flow and storage characteristics. Water inflow is randomly variable and is usually measured as precipitation, streamflow, runoff, or recharge. Storage, while not completely fixed, is much less varied and is usually measured by the volumetric capacity of reservoirs. Thus, the calculation of the safe yield of a surface-water supply system involves explicit dependence on probabilistic statements regarding rainfall and runoff. The conceptual difficulty here is that "supply" cannot be unambiguously defined except in reference to the probabilities of occurrence of a particular set of climatic events. Thus, we could for a given stream, readily construct a function relating to any particular streamflow the probability that at least that level of flow would be attained over any period. Then, in the absence of storage considerations, we could adopt some particular level of assurance (say 95 percent) and consider the corresponding flow as our "safe yield."[4]

Conceptually, the introduction of storage changes only the level of flow which can be attained with given assurance on the same stream (in, of course, the same climate). As the level of storage provided approaches infinity, the assured flow approaches the long-term mean flow of the stream. It is, however, important to bear in mind that the safe yield thus arrived at for a given stream and given storage is "safe" only to the extent that we consider the chosen probability level of assurance safe. There is no absolute safety here; the safe yield is *not* a minimum flow for the stream. Indeed, in principle the minimum flows for most streams are zero, although

[3] For the three water systems we studied which exhibited this characteristic pattern, new increments of supply were added, on the average, every 13 years, and the average size of the increments was 16 percent when measured against total safe yield existing at the time of addition.

[4] Here, too, we deal primarily with average annual flows.

the probabilities associated with extreme events in the neighborhood of zero flow are, for good-sized streams in humid areas, very small.

In practice, of course, we are not supplied with such complete information as that hypothesized above, and the practical difficulties of obtaining safe-yield estimates for particular streams are great. This is primarily the result of the fact that we have only a sample from the universe of possible streamflows for any particular stream. Hence, the best we can do is to estimate with more or less confidence the parameters of the streamflow frequency function. An additional important difficulty is, however, our lack of knowledge of the form of this frequency function. In particular, the question of the degree of serial correlation of streamflows has great bearing on the amount of storage needed to produce a given flow at a particular assurance level on a given stream.

In response to these difficulties, a number of methods of estimating storage/yield relations have been developed. The seminal work in the field was that of Rippl, in 1882.[5] His methods were subsequently extended by Hazen to cover more accurately the kind of problems actually faced by engineers.[6] These techniques have been further refined,[7] and now techniques are available for extracting a larger portion of the information from available streamflow records. One relatively new tool useful in this application is the estimation of complicated streamflow frequency functions from the records and the generation from these functions of long traces of "synthetic hydrology."[8]

More commonly used in practice is a method of estimating storage requirement which singles out a "design drought," or some specific period of historic low flows. Reservoirs are, then, designed to provide the required flow even under the precipitation/runoff conditions existing during the design drought. The required flow is then a "safe" yield in some probabilistic sense as discussed above, though here the probability statement remains implicit until the recurrence frequency of the design drought is analyzed.

[5] For an exposition of the Rippl method see Arthur Maass et al., *The Design of Water Resource Systems* (Cambridge: Harvard University Press, 1962), Ch. 3.

[6] Allen Hazen, "Storage to Be Provided in Impounding Reservoirs for Municipal Water Supply," *Transactions, American Society of Civil Engineers*, 77 (1914), 1539–1640.

[7] See, for example, Charles E. Sudler, "Storage Required for the Regulation of Streamflow," *Transactions, American Society of Civil Engineers*, 91(1927), 622; and M. B. Fiering, "Queuing Theory and Simulation in Reservoir Design," *Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division*, 87, No. HY6 (1961), 39–70.

[8] M. M. Hufschmidt and M. B. Fiering, *Simulation Techniques for Water Resource Systems* (Cambridge: Harvard University Press, 1966).

It is this method which has been used to calculate the safe yield of almost all watersheds in Massachusetts. In 1914, the New England Water Works Association published the results of an exhaustive empirical study of watershed yields in the northeastern United States derived from the performance records of 22 drainage areas.[9] From these records were developed a series of curves which depicted the amount of storage capacity required to obtain specified yields of runoff in the watersheds studied, with variable amounts of the total watershed area being water surface. The runoff or yield in these curves is expressed in number of gallons per square mile of watershed. Of primary significance to this report was the fact that the lowest recorded flows on Massachusetts streams up to that time, and also the lowest series of low flows, had occurred during the period 1908–11 and were included as examples of the minimum flows "likely" to be experienced in the watersheds studied.

The importance to our study of this method of estimation is that it pegs the level of supply assurance for Massachusetts cities and towns in terms of the hydrologic severity of the 1908–11 drought. This allows us to discuss not only the likelihood of more severe events but also how much more severe such an event would be. Thus, not only can we say that the 1908–11 drought appears to have a 3 percent chance of recurrence and the recent drought about a 1 percent chance,[10] as shown in Chapter 6 below, but we can also associate with each drought a value for one or more variables which may serve as climatic indices.

In carrying out the specification of our model, we will find it convenient to turn to precipitation-based indices for climatic surrogates. A key hypothesis of the study will be that there is a fixed relation between the severity of a drought relative to the design drought (measured in terms of our index) and the level of the demand/supply (demand/safe-yield) ratio at which systems will begin to suffer shortages on account of the drought. This contention puts some analytical content in the general statements made above concerning the likelihood of shortage for towns with differing demand/supply relations. The complete discussion of this matter will be set out in Chapter 6.

[9] "Report of the Committee on Yield of Drainage Areas," *Journal of the New England Water Works Association*, XXVIII (1914), 416.

[10] Because of the records we use in estimating these recurrence chances, we must say that the chance of recurrence of the 1908–11 drought is 7 out of 100 draws from a sample of 100 overlapping 4-year periods; that is, 1900–1903, 1901–04, 1902–05, 1903–06, etc.