CHAPTER 1

RESEARCH AS AN AID TO WATER SUPPLY PLANNING

The social sciences must depend largely on natural, uncontrolled experiments for obtaining data about the world they are attempting to describe and for testing theories they develop about cause-and-effect relations in that world. The economist, for example, is provided a rich source of data on prices, wages, and interest rates by the day-to-day functioning of the market economy.

But relying on the uncontrolled flow of the world's events presents a problem, because most of the systems being observed in the human social and economic world are seldom very far from equilibrium, and hence observations made on the parameters of these systems tend to be clustered in a small part of their potential ranges. This implies difficulty both in formulating and in testing theories to account for extreme events and forces the social scientist to question the generality of his results.

There is, however, one part of our world which, with some consistency, does introduce relatively extreme variation into the parameters of human social and economic systems. This is "nature," which through events such as floods, hurricanes, tornadoes, and blizzards disrupts production, transportation, and sales within the economy, introduces stresses into the general scheme of social relations, and produces pressures for both immediate and long-term actions by various levels of government. Thus it is not surprising, even on this very general level, that such events, often referred to as "natural hazards," have come to be recognized as fruitful fields of research for several branches of social science.[1]

[1] For an introduction to the existing natural-hazard research literature, see Ian Burton, Robert W. Kates, and Gilbert F. White, *The Human Ecology of Extreme Geophysical Events*, Working Paper No. 2, Natural Hazard Research Series (Toronto: University of Toronto, 1968, mimeo.). Examples of studies of specific hazards are:

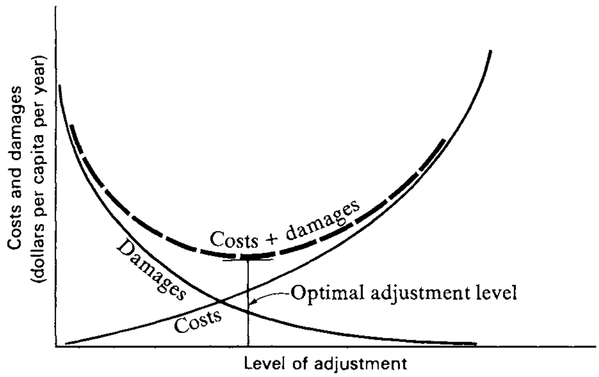

Figure 1. Adjustment to natural hazard: the problem.

Studies of natural hazards have a more tangible payoff than increased understanding of how various social systems function under stress. Any of these hazards imposes costs on society, most obviously in the forms of injury, loss of life, destruction of property, and diversion of effort to clean up and repair, but just as surely in the form of higher levels of tension and anxiety for the individual and for the group. Since certain natural events will continue to occur, the problem is to identify the best possible adjustment to these events on the part of society[2] and, since all adjustments have costs, to minimize the sum of these costs and the residual damages of the

(1) S. D. Flora, *Hailstorms of the United States* (Norman: University of Oklahoma Press, 1956); (2) R. Henrick and D. Freedman, "Potential Impacts of Storm Modification on the Insurance Industry" in *Human Dimensions of Weather Modification*, W. R. D. Sewell, ed., Department of Geography Research Paper No. 105 (Chicago: University of Chicago Press, 1966), which discusses hurricanes, tornadoes, hail, wind, thunderstorms, and extra-tropical windstorms; (3) U.S. Department of Commerce, Environmental Science Services Administration, *A Proposed Nationwide Natural Disaster Warning System* (Washington: U.S. Government Printing Office, 1965), especially pp. 25–37, which covers floods, hurricanes, tornadoes, lightning strikes and fire, earthquakes, and tsunamis; (4) U.S. House of Representatives, *A Unified National Program for Managing Flood Losses*, House Document 465, 89th Cong., 2nd Sess. (Washington: U.S. Government Printing Office, 1966), p. 3.

[2] "Adjustment" here is used in the widest sense to cover any action society or an individual may take to reduce the costs of an occurrence of the specific hazard in question, involving the construction of dams, dikes, or sea walls, the provision of warning systems and rescue units, the underwriting of insurance to affect the variance of losses, and many other actions. To assume that certain natural events will occur (probably according to some random distribution in time and space) is not to assume away such adjustments as weather modification; it is merely to move our concern back to levels at which we lose control. In this example, certain climatic patterns make weather modification seem attractive; we assume the climatic patterns are beyond man's control at least for the present.

event adjusted to. Clearly, then, one very important role of research in natural hazards is to provide data on the damages resulting under various levels of adjustment and, by extrapolation from the existing situation, on the damages to be avoided by further adjustments. This information is vital to any attempt to seek the optimal level of adjustment in the face of a given distribution of natural events.

Graphically, the situation may be characterized as in Figure 1. Damages are seen as a decreasing function of the level of adjustment and the costs of adjustment as an increasing function of that level. Observation of a specific occurrence (or series of occurrences) hopefully provides us with information on the extent of damages suffered under particular levels of adjustment, the costs of which are known. We are thus in principle able to estimate the two crucial functions and hence to find the optimal level of adjustment.[3]

This study is an example of such uses of the data generated by a natural event: the 1962–66 drought in Massachusetts, which was part of the drought experienced by the whole northeastern section of the country. The Northeast Drought began in 1961 or later, depending on location within the region. Rainfall had returned to normal by the end of 1966 for most of the region. The drought was, then, roughly 5 or 6 years in duration.

The amount of the precipitation shortage was also variable within the region. In general, the deficit amounted to about one year's rainfall over the 5- to 6-year period.[4]

The fact that a considerable proportion of the nation's population and industrial capacity is located in the Northeast had an important bearing on the widespread publicity about the drought. National concern was evidenced by hearings in the U.S. Senate and by a series of reports to the President by the Water Resources Council.[5] Several federal agencies assayed the situation as the drought deepened.[6]

[3] This discussion, in the interest of simplicity, does not deal with problems raised by uncertainty itself, with perception of hazard by individuals, or with "readjustment" by individuals to previous collective adjustment (such as in increased construction on plains behind flood walls).

[4] For example, at Pittsfield, the average annual precipitation is 40.6 inches, which would amount to 203.0 inches for a 5-year period. Over the years 1962 through 1966 the accumulated rainfall amounted to only 160.8 inches, making a deficit of 42.3 inches for the period.

[5] U.S. Water Resources Council, *Report to the President*, *Drought in Northeast United States*, July 21, 1965; *Report to the President*, *Reappraisal of Drought in Northeastern United States*, September 7, 1965; and *Report to the President*, *Drought in Northeastern United States*, *a Third Appraisal*, March 1, 1966 (Washington: U.S. Government Printing Office). The U.S. Water Resources Council is a cabinet level agency, established by the Water Resources Planning Act of 1965, to be responsible for coordinating federal water resources planning, policy-making, and action programs.

[6] A concise discussion of the hydrologic consequences of the drought, especially its

The drought's major impact was on municipal and industrial water supplies, since the Northeast is largely urban and industrialized, although damage to crops and livestock was heavy in limited areas of the region. Most widely publicized were the emergency conditions in New York City. But the same severe conditions existed throughout the region. Indeed, for most of the Northeast, the drought was the worst in recorded history when measured by the common hydrologic indices.

While it would have been highly desirable to study the effects of the drought on the whole Northeast, the research being reported was limited to Massachusetts primarily for reasons of convenience and economy. Two of the investigators (Kates and Arey) were then at Clark University in Worcester, which is in the approximate center of the state. Available time and travel funds promised to produce a maximum amount of data when expended within the relatively small area of Massachusetts. A number of other local characteristics were useful for a study of the drought. Long records of flow and runoff are available for several Massachusetts rivers, along with even longer series of rainfall records from stations over the state. The municipalities themselves are generally rather old and often have water systems records, including the reports of consulting engineers, reaching back into the 19th century. Most of these records are comparable over their lengths, for both the decision-making process of the local government and the hydrologic estimates which serve as guides in the process have remained unchanged for long periods.[7] In addition, there were available the records and planning experience of a much younger governmental entity, the Metropolitan District Commission, which, through a series of very large reservoirs and other works, supplies water to parts of the Boston metropolitan area, with an estimated total population of about 1,650,000.[8]

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effects on streamflow and groundwater, is to be found in H. C. Barksdale, Deric O'Bryan, and W. J. Schneider, "Effect of Drought on Water Resources in the Northeast," *Hydrologic Investigations Atlas*, HA 243 (Washington: U.S. Government Printing Office, 1966). The U.S. Army Corps of Engineers instituted a program of status reports originated by the regional Engineer Divisions to the Chief of Engineers in Washington.

[7] The decision-making process has not changed substantially since the city fathers of Boston debated the merits of alternative plans by a consulting engineer in 1825. See Daniel Treadwell, *Report Made to the City of Boston, on the Subject of Supplying the Inhabitants of that City with Water* (Boston: True and Greene, 1825). Quoted in Nelson M. Blake, *Water for the Cities*, Maxwell School Series III, p. 174 (Syracuse: Syracuse University Press, 1956).

[8] The Metropolitan District Commission, hereinafter referred to as the MDC, is a governmental unit chartered by the Commonwealth of Massachusetts. The MDC has three main divisions, Parks and Recreation, Sewerage, and Water Supply. The Water Supply Division provides water for the city of Boston and 31 other municipalities, most of which are in the Boston suburban area. In addition to supplying water for its member communities, the MDC supplies water when needed on an emergency basis to several other municipalities where the physical facilities for such transfer exist.

METHODOLOGY OF THE STUDY

With such records available, what could the tools of social science produce from them that would be of significance in planning to meet such a natural hazard in the future? First, we extracted data on the losses to be expected from water shortage in a municipal water supply system at various levels of the "adjustment" of that system. Broadly speaking, adjustment was measured in terms of the amount of water storage in the system relative to the projected demand for water at the historically given price, assuming a particular distribution of natural events in terms of rainfall. Since the expected losses vary inversely with the size of storage relative to demand, and since it was possible to estimate the costs of providing storage and to project future demands, it was possible to generate the two functions required for determining the optimal level of adjustment.

Our second major step, then, was to combine our estimates of expected losses and of costs of adjustment (construction of storage) in the appropriate optimizing framework. Specifically, we constructed a planning model for which we sought combinations of timing and size of increments to water system storage which would minimize the discounted sum of construction costs and expected losses from water shortage.

These results were then used to construct sample rules of thumb for planning the expansion of water systems. That is, a method was indicated for translating the solutions of fairly complicated programming models into terms which could be summarized in handbook pages for the use of practical planners.

Finally, these rules of thumb for decisions on the size and timing of increments were compared to the records of actual expansion decisions made over about 70 years by several Massachusetts cities.

The 237 Massachusetts communities which have their own water supply system and are not served by the Metropolitan District Commission formed our universe. All were surveyed initially with a one-page questionnaire, to which 156 replies were received. Fifty communities were then chosen for intensive interview surveys which concentrated on the characteristics of the municipal water supply system. Forty-eight of these interviews were completed. Tables 1 and 2 summarize the stratification of this sample of intensively studied water supply systems by size of population served, type of source, and type of adjustment to drought chosen by the municipal government.[9] Figure 2 shows the location of the 48 study communities.

[9] When the original sample was chosen, it was not realized that groundwater sources would be so difficult to fit into the conceptual framework of the adjustment-impact model developed below.

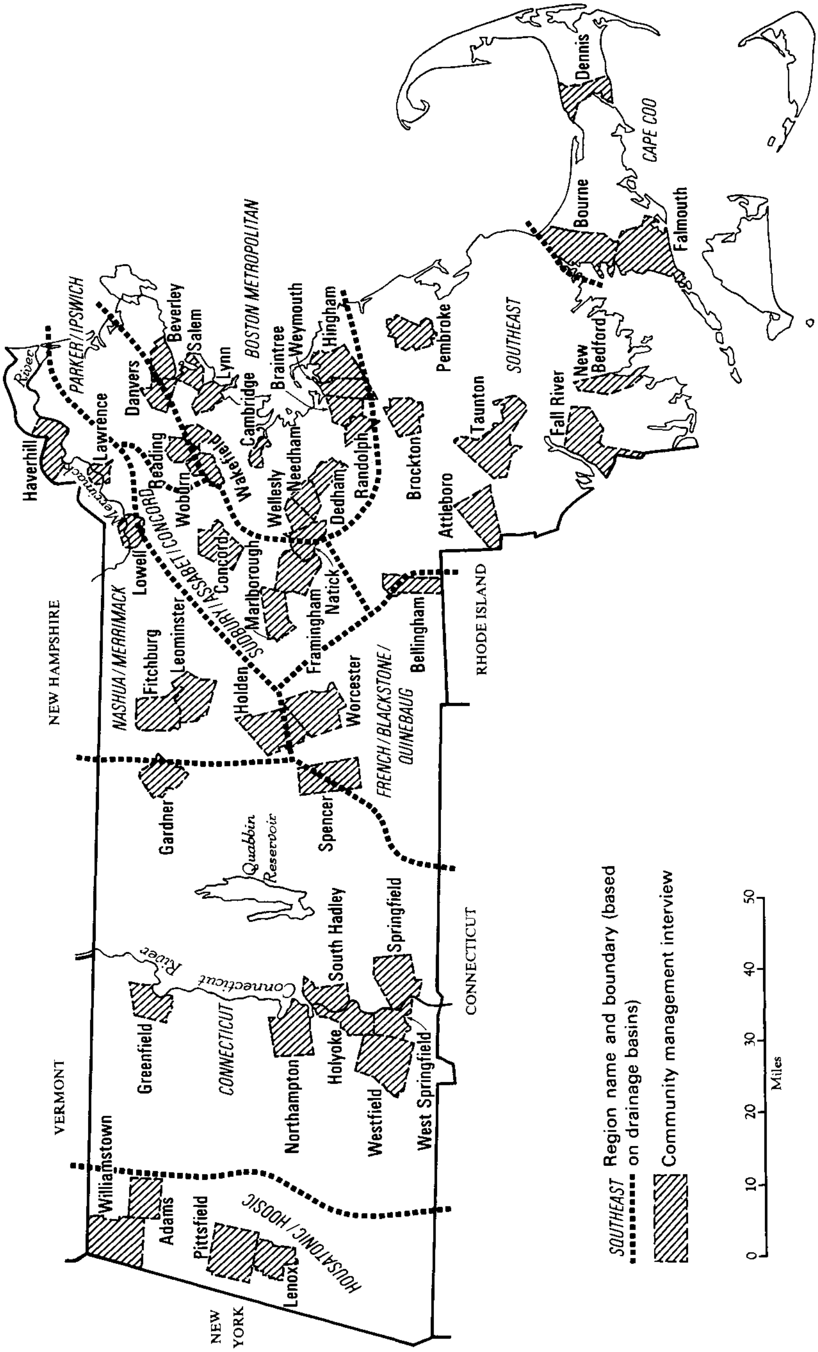

Figure 2. Location of 48 study sites.

TABLE 1. WATER SUPPLY SYSTEMS IN DETAILED SURVEY: BY POPULATION SERVED AND TYPE OF ADJUSTMENT

Population served	Number of systems	No adjustments	Restrictions on use	Increases in supply	Total number adopting some adjustment
5,000–25,000[1]	18	3	10	9	15
Over 25,000[1]	30	6	24	14	24
Total[1]	48	9	34	3	39

[1] Some communities adopted more than one type of adjustment; hence the totals do not check across the rows.

From these 48 communities, three were chosen for detailed investigation of drought losses. These were Braintree, Fitchburg, and Pittsfield. The survey methods included interviews with all managers of industrial and commercial firms of over 50 employees who claimed to have incurred costs or losses because of the drought; interviews with various public officials who had knowledge of municipal government expenditures in connection with the drought; and reviews of local newspaper files for the drought period. These several layers of sampling and the major studies conducted at each level are recorded in Table 3.

Finally, certain more specialized studies were conducted, as recorded in Table 4. The survey of the engineering reports made to the governments of 4 cities was conducted to give us a base of actual decisions on system expansion against which to compare our planning prescriptions.

THE PLAN OF THE BOOK

We begin by discussing in Part I the definition and measurement of the level of system adjustment. We use as a measure of system adjustment the ratio of system demand (at the historically given price set) to safe yield, a probabilistic measure of supply capability in the face of previously observed distribution of climatic events. This ratio is an indicator of the system's relative inadequacy. The higher the ratio, the smaller the supply capability relative to the predictable demand. After Chapter 2, which deals more carefully with this demand-supply measure of inadequacy, we spend two chapters discussing the components individually; in Chapter 3 we go into the concept of the safe yield of a surface water supply system,[10] while in Chapter 4 we explain our methods of measuring the demand for water

[10] We do not deal in this study with groundwater systems, primarily because of the difficulty of defining and measuring safe yields for them.

TABLE 2. SELECTED CHARACTERISTICS OF WATER SUPPLY SYSTEMS IN DETAILED SURVEY

		Primary Source			Average Consumption			
Population served	Number of systems	Surface water	Ground water	Combined groundwater and surface water	Total daily 1950–62 (million gallons per day)	Per capita daily 1950–62 (gallons per day)	Per capita daily 1963–66 (gallons per day)	Average charge per 1,000 gallons[a] (cents)
5,000–15,000	12	2	5	5	0.7	90	95	39.5 (6 systems)
16,000–25,000	6	3	3	0	1.6	94	100	21.0 (2 systems)
26,000–75,000	21	9	5	7	4.2	119	137	26.5 (13 systems)
Over 75,000	9	9	0	0	14.2	123	139	20.7 (4 systems)
Total	48	23	13	12		106[b]	118[b]	

Source: Interviews with 48 water system managers and the files of the Massachusetts Department of Public Health.

[a] Where data were available, the average charge per 1,000 gallons was derived by dividing total community water revenues by the number of gallons sold.

[b] Simple average.

TABLE 3. SUMMARY OF DATA SURVEYS

Public water supply Systems (Total in state: 237)	Water system characteristics	Drought impact and adjustment	Hydroclimatological data	Other socioeconomic data	Major sources
184 cities and towns	Safe yield; population served (where available)	Adequacy of system estimate	Monthly Palmer Drought Index for entire state 1929–66 (for 150 cities and towns, information on restrictions and emergency supplies)		Mail questionnaires; 1963 USPHS inventory[a]
48 cities and towns (including all over 25,000 not in Massachusetts District Commission)	Supply-demand characteristics; annual water use 1950–66; monthly water detailed use 1960–66; rates; financial structure	Adequacy of system; managerial perception; adjustments	Monthly Palmer Drought Index for entire state 1929–66 (for 150 cities and towns, information on restrictions and emergency supplies)	Estimated population; employment index 1950–66	Interview with water manager; Massachusetts Department of Public Health reports
Braintree Fitchburg Pittsfield	Demand, actual consumption, safe yield 1950–66	Detailed drought losses		Attitudes of community leaders and municipal decision-makers	Interviews with municipal, commercial, industrial leaders; newspaper files

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

TABLE 4. SUMMARY OF SPECIALIZED DATA SURVEYS

System	Water system characteristics	Drought impact and adjustment	Hydroclimatological data	Socioeconomic data	Major sources
Fall River Fitchburg Pittsfield Worcester	See Table 3; demand, actual consumption, safe yield 1929–66		Annual precipitation 1867–1966 at 5 stations; stream-flows as available	Municipal debt, 1907–62; employ-ment, 1929–66	Interviews; Massachu-setts Department of Public Health re-ports; engineering reports
Metropolitan District Commission (MDC)	Actual consumption, safe yield	Measure of restric-tion effects	None specific to MDC		Interviews, literature, public documents
Miscellaneous	Water-use/safe-yield ratios	Attitudes of state officials and con-sulting engineers	New Bedford Palmer Drought Index 1812–1967		U.S. Public Health Service inventory; interviews

at existing prices using the available data for the pre-drought period. We are interested here in identifying a relation for each community between the level of per capita demand and the values assumed by various explanatory variables.

In Chapter 5 of Part II, the empirical relations of Chapter 4 are used to project demand into the drought period. These projections, in turn, allow a working definition of the level of *water shortage* suffered in a year by a system: Shortage equals the difference between the *projected demand* for the year and the *amount of water actually delivered* by the system. (In looking into the future, actual deliveries are replaced by the amount of water available for delivery.)

The size of the shortage suffered in a dry year by a system having a given inadequacy level will naturally depend on the severity of the climatic event occurring in that year—how dry the dry year really is. In Part II, Chapter 6, we discuss the measures of climatic variation which are used in our model. Having defined and measured the physical severity of drought in a particular community and year, we set out a model linking these climatic conditions with water system inadequacy and the amount of shortage. This is the concern of Chapter 7. The evidence developed by this study on the relation between shortage, inadequacy, and climatic variation is then examined. Finally, in Chapter 8, we consider *possible* adjustments to impending shortages on the part of water system managers. Evidence is then presented on the adjustments *actually* adopted in Massachusetts during the recent drought.

Part III of the work deals with the measurement of losses attributed to the drought in three Massachusetts cities, and with the relation between these losses and the levels of potential water shortage which caused them. After discussing in Chapter 9 the methods used in obtaining raw-loss estimates from our sample communities and displaying these estimates, we apply, in Chapter 10, corrections for several important economic considerations: the returns to drought-induced investment, the appropriate accounting stance, and the effect of deferral or transferral of production and sales.

Chapter 11 presents a summary of corrected losses suffered by customers of the municipal system (and by the municipality itself) in annual per capita terms. These figures are then combined with probabilistic climatic data to derive expected-loss functions which can be used in the planning model. The expected-loss functions represent the ultimate payoff from the study of the drought itself. The remaining chapters of the book discuss the application of these results to the planning of municipal water supply systems.

In Part IV, we derive cost-of-safe-yield functions and combine these with the expected-loss functions to form a capacity expansion model designed to determine the optimal size and timing of increments to a water supply system.

The final part of the volume (V) deals with practical water system planning. We begin by deriving two sets of rules of thumb for practical planning based on the results obtained from the planning model. These rules permit managers to plan for approximate optimality (in terms of the capital-cost/drought-loss trade-off) for given estimates of the rate of growth of population and the appropriate discount rate. We then discuss the process of planning and decision-making for the water supply system as actually observed in the context of municipal government. Finally, we examine historical records to see what can be said about the actual paths of the five systems studied in comparison with the paths implied by the rules of thumb.

A final chapter summarizes our findings about the drought and gives our suggestions for improving the planning process. Here, as elsewhere, we touch briefly on some of the very real obstacles to planning solely on the basis of economic considerations. The brevity of the discussion should not be taken to imply that such obstacles can be assumed away.