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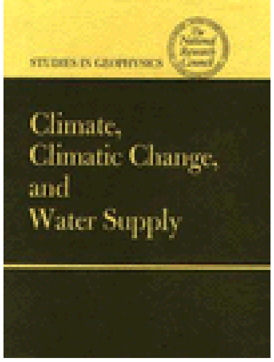

Climate, Climatic Change, and Water Supply

Panel on Water and Climate, Geophysics Study Committee, Geophysics Research Board, National Research Council

ISBN: 0-309-56789-0, 132 pages, 8.5 x 11, (1977)

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Climate, Climatic Change, and Water Supply

STUDIES IN GEOPHYSICS

Panel on Water and Climate
Geophysics Study Committee
Geophysics Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1977

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by the Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The Geophysics Study Committee is pleased to acknowledge the support of the National Science Foundation, the U.S. Geological Survey, the Energy Research and Development Administration, the National Oceanographic and Atmospheric Administration, the Defense Advanced Research Projects Agency, and the National Aeronautics and Space Administration for the conduct of this study.

International Standard Book Number 0-309-02625-3
Library of Congress Catalog Card Number 77-82828

Available from
Printing and Publishing Office

National Academy of Sciences 2101 Constitution Avenue Washington, D.C. 20418

Printed in the United States of America

Preface

Early in 1974, the Geophysics Research Board completed a plan, subsequently approved by the Committee on Science and Public Policy of the National Academy of Sciences, for a series of studies to be carried out on various subjects related to geophysics. The Geophysics Study Committee was established to provide guidance in the conduct of the studies.

One purpose of the studies is to provide assessments from the scientific community to aid policymakers in decisions on societal problems that involve geophysics. An important part of such an assessment is an evaluation of the adequacy of present geophysical knowledge and the appropriateness of present research programs to provide information required for those decisions. Some of the studies place more emphasis on assessing the present status of a field of geophysics and identifying the most promising directions for future research. Topics of studies that are now under way include geophysical predictions, upper-atmosphere geophysics, energy and climate, water and climate, and estuaries.

Each study is developed through meetings of the panel of authors and presentation of papers at a suitable public forum that provides an opportunity for discussion. In completing final drafts of their papers, the authors have the benefit of this discussion as well as the comments of selected scientific referees. Responsibility for the individual essays rests with the corresponding authors.

The essays in this volume were presented in preliminary form at an American Geophysical Union meeting that took place in Washington, D.C., in April 1976. Their subject matter is wide ranging, dealing not only with climate, weather, and water but also with water-resources planning, water law, and the economic and societal impact of water shortages.

The introductory chapter provides an overview of the study summarizing the highlights of the essays and formulating conclusions and recommendations. In preparing it, the chairman of the panel has the benefit of meetings and discussions that take place at the symposium and the comments of the panel of authors and selected referees. Responsibility for its content rests with the Geophysics Study Committee and the chairman of the panel.

Panel on Water and Climate

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INTRODUCTION

The earth's climate is changing, and associated predictions of future floods and droughts reverberate throughout the news media. Coupled with forecasts of climatic change, one can often find associated predictions of social unrest, wars, and famines, but these possible derivative issues are not addressed in this volume. The papers consider only the simpler problems of water shortages, which may or may not be severe enough to be classified as droughts and which may or may not have resulted from climatic change, as well as make an assessment of the probable effects of climatic variability and climatic change on the nation's water supply needs, policy, and design.

Lack of water hampers population and economic growth in some areas of the world, but even in such areas it is common to think of water as a resource that is renewable within the bounds imposed by a stationary regional climate. Unexpected, prolonged, and widespread shortages of water resulting from climatic change could have an unsettling and depressing effect on regional and possibly even on the national economy. In spite of the foregoing, it is now the opinion of this panel that there is small probability of a change in regional climate so abrupt, widespread, severe, and statistically unambiguous that current water-resource design practices need or should be radically altered. However, the probability of such a change is not zero, and there is a great deal that could be done now that would allow for mitigation of the effects of possible climatic changes on future water supplies.

The papers in this volume do not call for sudden, massive inputs of new federal, state, and local funds to builds reservoirs, canals, and other water-resource structures to alleviate droughts caused by climatic changes. To advocate such action programs without making comparative analyses of the other long-term hazardous shortages facing the nation would not be particularly productive, while to make such complete analyses was clearly beyond the mission of this panel.

What has been attempted in this volume is to evaluate the interactions between hydrology, water supply, climate, and climatic change and to highlight areas where deficiences in knowledge and data make rational water-resource decision-making more difficult than it needs to be.

Solving even the limited objectives outlined above is complicated. The evaluations embrace not only the geophysical disciplines of meteorology and hydrology but also societal, legal, engineering, and economic questions that are quite difficult to resolve in their own right. A further complication to a rational study of climatic change and water supply is the aura of uncertainty that hovers over all who try to predict the future on the basis of limited data and understanding. The disciplines of probability and statistics and the fields of computer modeling and decision theory all impinge on the evaluations that are offered. With such a complex subject, a single person has difficulty encompassing all the needed specialties. Hence, the papers in this volume are from authors from diverse disciplines, each paper reflecting the individual author's background in one or more of the disciplines relevant to the overall issue of future climate and water supply. There is little overlap among the papers and little that should be omitted, although, as might be expected, common themes and recommendations do appear in many of them from time to time.

CONCLUSIONS AND RECOMMENDATIONS

1. Barring totally unforeseen circumstances, the United States can expect to experience periodic, local, severe water shortages.
2. Very little information is available on the sociological and economic implications of droughts, Are the solutions imposed permanent or temporary, and what would the optimum strategy be for a community facing a water shortage? A series of studies that focus on the adequacy of future water supplies and water-transfer systems relative to demand under adverse conditions should be initiated. That is, research on the resilency of water-resource systems is needed.
3. The transfer functions from climatic forecast to water-supply values are still embryonic and need to be improved greatly.
4. The transfer functions and the climatic-index variables to get from climatic forecast to crop yield are not yet known for many crops and localities. Interactive research between climatological forecasters and crop specialists is needed.
5. The conflicts resulting from future water shortages, whether from natural climatic variability or climatic change, could be alleviated by adjusting water law along the lines suggested in the 1973 National Water Commission report, *Water Policies for the Future*. In particular, federal reserved rights should be eliminated, and Indian water rights should be identified and quantified.

6. In order to project future water demands in a comprehensive fashion for a region, a series of regions, and ultimately the nation, a multisector economic framework should be established for some base year. Within this framework a consistent set of economic activity levels should be developed; and water-use data, disaggregated by end-use, should be organized to include information relating to self-supplied and publicly supplied water, demand elasticities for those sectors as applicable, and technological considerations. The need for such a data base becomes particularly great when we wish to consider probable changes in water demand associated with future climatic changes, the expansion of irrigated agriculture and supplemental irrigation water supplies in the dry farming areas of the United States, or both.
7. Paleoclimatic research offers a promising approach to better estimates of past climatic variability and drought probabilities. This type of research can be justified on the grounds that it may help in producing more robust water-resource systems.
8. Future water shortages may be exacerbated by climatic change, but unfortunately the climatologist's current forecast ability is insufficient to aid the water-resource planner or hydrologic designer. To be useful to water-resource planning, climatic-change forecasts would need to be specific by area and be accurate over the 50 to 100 year design-life of the water-resource system, offset by the additional 10 to 30 years that are needed to plan and build the system. There is no evidence that such a forecast ability either exists or will appear within the immediate future. Research on deterministic physics-based climatologic modeling and climatic change should continue, as it may eventually help to provide the necessary scientific justification for proposed snow-augmentation programs.

HYDROLOGY AND WATER-RESOURCE DESIGN

There is undoubtedly a definite relation between the storage provided by an impounding reservoir on any stream and the quantity of water which can be supplied continuously by it. The relation, however, is a complex one, and our knowledge of its character is limited. ——Allen Hazen, 1913

There are very few certainties in water-resource design and even fewer studies in which the effect of various uncertainties on the water-resource design process have been evaluated. A pioneering study that used a four-way analysis of variance to partition the total variance between four planning variables[1] concluded that uncertainties in the economic projection were of prime importance and hydrologic uncertainties were of the least relative importance to the water-resource planning process. Unfortunately, there has been little or no follow-up work of a similar nature, and the case for the relative unimportance of hydrology should not necessarily be extended to situations of heavier demand or areas of more uncertain supply.

The uncertainty of hydrology in water-resource design arises because hydrologists are unable to forecast the future sequence of flows that any proposed water-resource structure will encounter during its design life. However, this is of little concern as long as the natural supply is large and stable and the demand relatively low. Under such favorable conditions, the chance of shortages occurring within the lifetime of a proposed water supply system are minimal and may be safely ignored. Critical water shortages arise when the regional demand increases to an appreciable portion of the long-term expected mean supply, for then seasonal and longer period variability in the natural flows causes shortages to appear. Prolonged periods of water shortage are popularly referred to as "droughts," and it is the duty of the water-resource planner to circumvent droughts.

The basic philosophy used by all water-resource planners has been that the recent past is the key to the near future. The near future is easily defined as the design life of the proposed structure, while the techniques for defining the recent past have not been widely agreed upon and have even been the subject of some controversy. These specialized arguments will not be discussed here, but the interested reader can learn much from the papers by Stockton, Matalas and Fiering, Schwarz, and Dracup, and from their cited references.

As an overview of the issues, it is necessary that this introduction be over-simplified; hence the discussion that follows is restricted to annual flows and a set of hydrologic or climatologic properties that are believed to be related to most hydrologic designs. An attempt is made to show how these properties may be related to a set of hydrologic statistics whose values may be estimated and used in the design process.

From a set of annual streamflows $x_1, x_2, x_3, \ldots x_{T-1}, x_T$, the mean flow, $\bar{X}$, and its variability, S, called the standard deviation of the flows, may be estimated.[2] While it is obvious that these statistics must be related to water-resource system performance, they are in themselves insufficient because it is also necessary to consider the order of occurrence of the flows, that is, the tendency or lack of tendency for high flows or low flows to cluster.

More specifically, the capacity of the smallest reservoir that could be built, R^*, that would yield uniform outflow and become full only once and empty only once when subjected to a given sequence of inflows can be visualized as the absolute sum of the maximum negative, R^-, and positive, R^+, accumulative departures from the accumulative mean flow, as shown in Figure 1. Experience has shown that R^* is usually much too large to be used as the design variable for reservoir sizing, but shorter periods of critical low flow, *Cf*, selected from the sequence x_i have been used as design variables. R^* and C_f are statistically related and positively correlated. Hydrologists have always realized that *Cf* was itself a random variable, but it was not until the Harvard Water Program of the early 1950's that the importance of this concept was formalized. The Harvard Water Program used very long hydrologic sequences divided into many sequences of length equal to the proposed design life of the water-resource systems to arrive at designs that performed "better" with a variety of sequences and hence for a variety of *Cf*'s.

As sequences of the required length did not exist, the Harvard group used synthetic lag-one Markov sequences

$$x8_i = \rho_1 x_{i-1} + \epsilon_i,$$

where the ϵi are independent random variables scaled to preserve the observed means, variances, and lag-one correlations, ρ_1. Subsequently, it was found that these synthetic sequences, generated so as to be "equally likely to occur as the observed," actually tended to yield Cf values lower than those of the observed sequences; and a search was initiated for alternative generating mechanisms that would not display this undesirable property.

The search for alternative synthetic hydrologic generating mechanisms has three aspects: First, incremental changes to the basic lag-one Markov model such as correcting for biases in the parameter estimating procedures, or going to multilag models. Much of this work has been sound, as well as useful, but the basic problem has not been conquered by this approach. Second, the climatic change approach under which the basic lag-one Markov model is retained, but the parameters are changed according to the dictates of a master long-term climatic-change model. The overall result of this second approach is a nonlinear, nonstationary, synthetic hydrology that has not yet been made operationally useful and that will remain statistically suspect until the models of climatic change are based more closely on the laws of physics.

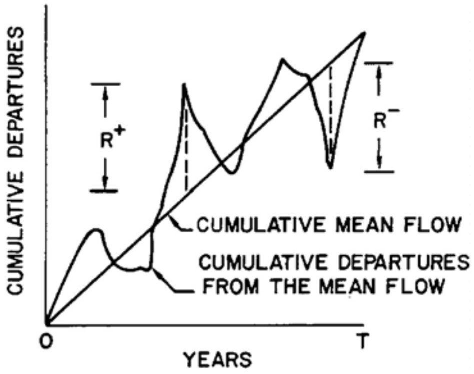

FIGURE 1 Definition of $R^* = R^+ + |R^-|$.

The third approach to generation of more realistic synthetic hydrologic sequences has been to use a radically different set of stochastic processes, namely, Mandelbrot's fractional noises[3] and approximations thereof, based on engineering judgment.[4] Fractional noises have the unusual property

$$R^*/s \sim n^h,$$

where n is the sequence length and h is a parameter of the fractional noise that can take any value between 0 and 1 except for 0.5. The usefulness of the exponent h is that most geophysical records and some laboratory experimental noises[5] have $h > 0.5$, while all stationary independent and short memory stochastic processes have $h = 0.5$. Fractional noises and their more developed approximations have been found to yield C_f values that are statistically indistinguishable from observed Cf's.

Water-resource system design is a complex and time-consuming process, and alternative designs, if prepared, represent discrete rather than continuous differences in design. The Harvard Water Program and its predecessors implicitly assumed constant climate and searched among alternative system designs for the “best” design, where best design was specified as that which maximizes the net benefits or minimizes the economic regrets. In this volume, Matalas and Fiering discuss the calculus of economic regrets in water-resource design in the light of possible procedural changes that could result from considering forecasts of climatic changes. In particular, they emphasize that unless the exact sequence of future flows can be predicted with certainty there may be little benefit to hydrologic system design of even an exact forecast of a change in one or more of the parameter values of the hydrologic input.

As previously mentioned, alternative system designs are discrete, with each design being the operational choice over a certain range of climatic parameters; hence the same design may still be the best choice under a changed climate. To allow explicitly for climatic change in the design process, Matalas and Fiering introduce and define the concept of “robustness.” A robust design may not be the optimal choice in the classical sense defined above, but it will be a design that performs reasonably well under a variety of possible climates. Further, Matalas and Fiering point out that the resilience of an existing well-buffered water-resource system can be enhanced by changes in insurance, subsidies, zoning, water law, and price structures, as well as by additional structural measures such as reservoirs, pipelines, and well fields. Resilience then is the property that allows a system designed for one climate and set of conditions to be modified in response to persistent new climates or other conditions. System resilience is probably quite variable, and to assess fully the consequences of climatic shifts, the tradeoffs among all the above resilience strategies would have to be evaluated and articulated.

Certainly, prolonged droughts caused by persistent demonstrable climatic changes could enhance the conflicts of interest between groups of water users. It is hoped that the resolution of such conflicts would be rational, with the resulting tradeoffs being acceptable to all—in other words, along what Matalas and Fiering have referred to as the Paretian frontier.

CLIMATIC VARIABILITY

> . . . The early part of the century (1907–1932) was one of anomalously high persistent runoff from the upper Colorado River Basin, apparently the greatest and longest in the last 450 years. This wet period was preceded by a long persistent low flow period during 1868–1892.
>
> —Stockton and Jacoby, 1975

Hydrologists have long appreciated that climate is highly variable over all time scales, and the sequences of observed river flow are unlikely to be repeated in future periods. It has been the evident uncertainty of future flows that has led U.S. hydrologists to appreciate long, accurate records and to design water-resource systems that are as robust as possible to the vagaries of climate. Further, U.S. water-resource systems, when finally built, have tended to be operated to maximize the individual system's resilience to climatic or other insults that the heavens or man impose.

While river flow is the primary symptom of climate that concerns the water-resource planner or the hydrologic scientist, it is not the variable that climatologists consider when they talk about climate, climatic variability, and climatic change. But even precipitation, a more "normal" index of climate than streamflow, has proved to be inexplicably variable; for instance, consider Figure 2, which shows the extreme differences in the long-term accumulative precipitation that have been recorded at four Canadian weather stations situated only a few miles apart in a topographically homogeneous region of ostensibly uniform climate. For the 80 or so years of record, annual precipitation in this region has varied from 7 to 27 inches. Total precipitation amounts for 10-year periods have varied by over 40 inches at fixed sites, while similar differences between adjacent sites for identical periods have also been observed. While it is known that persistent differences in the catch of two rain gauges situated only 10 feet apart can be as high as 50 percent because of differences in gauge exposure,[6] the meteorologists who have analyzed the data base of Figure 2 have been unable to detect any such biasing. The conclusion remains that point rainfall data in an arid region can be disconcertingly different for long periods of time, even at gauges that are spaced quite close to each other.

Global average temperature is probably the most studied and written about variable of climate. Over the last 1000 years, global temperature has fluctuated on the order of 1 1/2°C; and as Schneider and Temkin note in their paper, changes of this magnitude can be expected to influence global food production. But greater global temperature changes have occurred in the geologic past, and smaller changes in the more recent past.

For instance, consider the Mohonk Lake mean annual temperature displayed in Figure 3. Mohonk Lake is situated amid 5000 acres of largely unspoiled forested land owned by the Mohonk Trust of New Paltz, New York. The lake obtains its water from groundwater flow, and there are no surface streams.[7] From 1896 to 1950, there has been an increasing trend in the mean annual temperature observed at Mohonk Lake, and from 1950 onward a decreasing trend. Similar trends have been observed for most other weather stations in the United States and Canada.

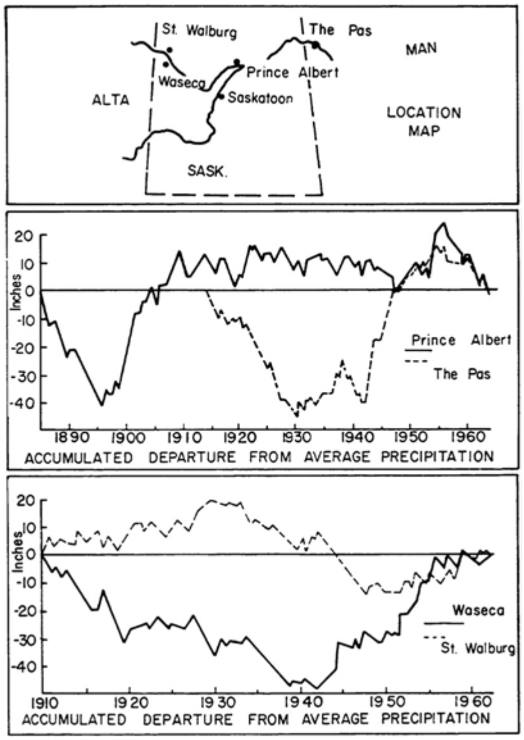

FIGURE 2 Cumulative departure from average precipitation for four Canadian weather stations. The figure illustrates that prolonged wet and dry periods can be observed for localities that are quite close to each other. When dealing with natural long-term climatic variability of this magnitude, it may be difficult for the water-resource planner to distinguish the effects of the climatic change reported by climatologists to have occurred during the late 1960's. Figure redrawn from a paper by G. A. McKay that appeared in the proceedings of the Saskatoon Water and Climate Symposium, November 1964 (Water Studies Institute Report No. 2, October 1965, Saskatoon, Sask., Canada).

The importance to water-resource design and operation of long-term time-dependent temperature changes of the magnitude shown in Figure 3 are not satisfactorily known. Further, as shown in the paper by Lofting and Davis, it may be quite difficult to make the necessary economic analyses without some reforms in the way that water-use data are currently collected and preserved, not to mention the additional difficulties associated with the climate-to-hydrology transfer functions (see later sections).

The prime hydrologic variable, water available for impoundment in a reservoir, can also be as variable as the usual climatological variables (precipitation, temperature, wind speed, cloud cover, etc.). In particular, long periods of high average flow and long periods of low average flow are the rule for rivers in arid environments. Further, as population and water use increase so does the likelihood of water shortages that are both more intense and more widespread than previously experienced. Nowhere in the United States is the future collision between available supply and projected use more apparent than in the upper Colorado River Basin, the subject of John Dracup's paper in this volume.

Two estimates of the adjusted-to-“virgin”-flow condition (that is, without upstream diversions and losses) have been made for the Colorado River at the Lee Ferry compact point for the period 1914–1965. The two estimates differ in details, but they are both in accord that the 52-year sequence of annual flows was much wetter in the period 1914–1933 [17.0 million acre-feet (maf)] than in the period 1946–1965 (13.3 maf). If we are to regard the hydrologic generating mechanism giving rise to these Colorado River flows as a stationary-independent or stationary short memory (say lag-one Markov) process, observed differences of this magnitude are very rare occurrences. For instance, consider the statistic

$$Z = |\bar{X}_1 - \bar{X}_2| / [(S_1^2 + S_2^2)/n]^{1/2},$$

where n is the period length and $\bar{X}$ and S are the respective period means and standard deviations and for which the above data yield Z = 2.88. If the two 20-year sequences are considered to have no cross correlation and to be sample functions from a normal independent process, then a value of Z as high as 2.88 could be expected to occur less than 1.0 percent of the time. Note that it is known that the Z statistic is insensitive to differences in the coefficient of skewness for a two-parameter log normal generating process and that considering the generating process to be lag-one Markov with low ρ_1 would not appreciably change the probability of observing such a high Z. A similar conclusion can be reached by considering the rescaled range, R^*/S, for the period 1914–1965 and comparing the observed value, 13.08, with density functions for R^*/S. In other words, low flow probabilities for the Colorado River Basin should not be assessed on the assumption that the annual events have been generated by an independent or short memory generating process. In fact, to do so would result in an underestimation of the regional drought hazard.

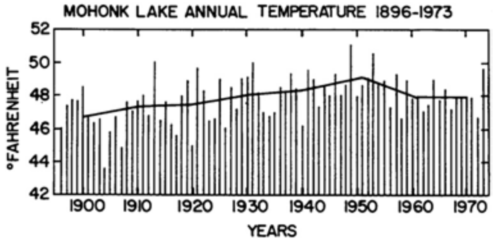

FIGURE 3 Annual temperature in °F for Mohonk Lake, 1896–1973, with a moving average trendline. The 1896–1950 upward-sloping trendline is statistically significantly different from zero trend at the 95 percent confidence level based on the assumption that the individual data points are independent of each other. Figure has been redrawn from the *Mohonk Trust Newsletter,* November 23, 1974. The Mohonk Trust is headquartered at Mohonk Lake, New Paltz, New York.

When a set of data sampled over time has statistical properties similar to the Lee Ferry adjusted virgin flow data, it is improbable that an accurate determination of the true long-term mean can be made by considering a record of only 25 observations. If the series is considered stationary, then the sample mean, $\bar{X}$, will indeed approach the long-term mean, μ, as the length of record increases; sequences taken from independent or simple Markov processes. Under the however, the rate of convergence will be much slower than that expected for above circumstances, the techniques of geochronology as outlined by Stockton should give a better estimate of μ than does $\bar{X}$. Based on tree-ring indices and regression, a 450-year-long record of estimated annual flows for the Colorado River has been prepared, and for this record the estimated long-term mean flow, μ, was 13.5 maf. Had this estimate of μ been available during the deliberations leading to the Colorado compact,[8] it is probable that little credence would have been attached to the estimate given the much higher known flow of the preceding 25 years. However, subsequent flows have averaged close to 13.5 maf, and the possible argument for ignoring the long-term estimate based on the magnitude of the previously mentioned Z statistic is no longer tenable.

Geochronology is a useful tool for relating climatology and hydrology, especially when estimates of the long-term mean are needed. However, the estimates of climatic variability derived from regressions are biased (see the Matalas and Fiering paper), and the uncertainties attached to extreme drought frequencies derived from geochronology are as yet unknown. Still, it is interesting to note that the 450-year reconstructed record shows that multiyear periods of low flow have probably occurred on all the subbasins of the upper Colorado in the fairly recent past and that these periods of low flow have not necessarily been in phase for the different subregions—a result reminiscent of Figure 2.

While the problems of future water shortages in the arid southwest are obvious and imminent, this is not the only area of the country where future water shortages are predictable. The paper by Schwarz considers the humid industrial northeast region and finds very low storage capacities for water. Rainfall tends to be comparatively evenly distributed throughout the year in the northeast, but occasionally successive years of low late-summer and early-fall rainfall occur; the most recent of these dry periods was the 1963–1967 New England drought. However, other severe dry periods of similar length have occurred on at least four different occasions in the last 230 years,[9] and it would be quite surprising if we did not experience similar shortages in the future.

In summary, available hydrologic and meteorologic records show that climate has been extremely variable in both space and time in the immediate past. Unless climatologists produce evidence to show that this past climate instability has lessened, it would be only prudent for resource planners to expect such variability to continue in the future. It is against this background of immense, often inexplicable, climatic variability that climatologists distill their signals of climatic change and develop their models for forecasting future climatic change. It is not an easy task.

LONG-RANGE FORECASTS OF CLIMATIC VARIABLES

. . . when somebody asks me what I think about the future climate, I usually say that the best way of showing that you are not a capable climatologist is to try to make a forecast. ——Bert Bolin, 1976

Not all meteorologists agree with Professor Bolin's view of climatic predictabilities, but his view does coincide rather closely with the official position of the American Meteorological Society[10] and also with the rather well-documented and carefully thought-out view expressed by the *ad hoc* Panel on the Present Interglacial.[11] However, this conservative view of climatic predictability has not been so well publicized as that of those who prophesy imminent climatic doom, and it appears likely that hydrologists and water-resource planners may not be aware of the tenuous scientific underpinnings of most climatic forecasts that are often based on what Gani has referred to as “poor foundations, apparent similarities, parallel-looking curves and analogous trends.”[12]

Intrinsically, there are two approaches available for long-range climatic forecasting. The preferable method is to understand the climatic system and all its relevant feedback mechanisms so thoroughly that it becomes possible to make a deterministic, physics-based model that reproduces the important features of different regional climates with sufficient accuracy to produce forecasts of future climatic events that are correct in both time and space. Models that include the key interactions between the elements of the atmosphere–ocean– polar ice cap system responsible for climatic change on various scales of time do not yet exist. Even when the models do exist, their reliability will be largely unknown and may hinge on factors that are totally external to the model, such as solar changes or explosive volcanic eruptions. In summation, physics-based, deterministic climatic forecastability does not yet exist at the detailed level that would be needed if a water-resource planner or manager wished to incorporate such forecasts into the decision process.

The second method of forecasting future climates is statistical. For instance, using a long paleoclimatic record (see the paper by Stockton), we could assign probabilities of going from the current climate to a different one based on certain assumptions about the distribution of intervals between transitions. This approach has not been used in water-resource design, probably because of the unreliability of transfer functions that would get the planner from the paleo-climatic index to the water-resource design variable, *Cf.* Another statistical approach is to take observed climatic records and look for past trends or cycles and then to use these as a basis for forecasting future events. However, as aficionados of the stock market have found, a chartist philosophy, basing forecasts on past trends and cycles without a solid understanding of the mechanisms that have given rise to the apparent trend or cycle, often leads to erroneous forecasts.

As an illustration of possible climatic forecasts that could be made based on trends, consider the previously presented temperature data of Figure 3. Climatologists have not yet agreed on the physical mechanism causing these trends, and it is doubtful that the existing data base is sufficient to support a mathematical modeling of the phenomena even if all the possible mechanisms were totally understood. It is obvious from Figure 3 that projecting in the late 1940's from the then-existing trend in temperature would have yielded an erroneous forecast, and hence projecting the present trend into a near-future mini ice age may not prove any more reliable. Further, we should point out that to the panel's knowledge the effect of these past long-term temperature trends on U.S. water supply and demand has not yet been either noticed or evaluated. How severe a global average-temperature change would have to be before a specific water-resource design would need to be altered is a subject for future research (see the papers by Matalas and Fiering, and Lofting and Davis).

Cycle analysis is also used as a basis for long-term climatic forecasts. The procedures use more sophisticated techniques than trend analysis to look for “significant” cycles in weather or other data and then to use these cycles as a forecasting algorithm for predicting future climatic anomalies. The tests of significance used are usually based on the implicit assumption of noncyclic independence in the data—an unlikely assumption for climatic data.[13] Further, it is experimentally verifiable that stochastic processes with low-frequency components can yield sample functions with numerous “significant” spurious cycles.[14] In addition, it is widely known that “significant” cycles are often introduced into the analysis by moving average manipulations to smooth what are otherwise noisy data.[15] In spite of those defects to cycle analysis, it is still a popular occupation among a portion of the forecasting community and even supports its own specialty journals, which contain discussions of cycle synchronies observed for almost all wavelengths and phenomena. As an example, consider:

> . . . the clustering of phenomena around for example: 4.0, 6.0, 8.0, 9.0, 9.2, 9.5, 9.9, 11.2, 12.0, 12.6, 16 2/3, 17 1/3, 17.7, 18.2, 22.0, 54.0, and 164 years, are substantiated by so many well established cycles that it seems improbable to explain these by statistical freaks only.[16]

More specifically, one may consider the long-range climatic forecasts made several years ago for the various locations in the United States.[17–19] A complicated algorithm was developed based on solar cycles of 91, 46, and 23 years and 91, 68, 55, 44 1/4, 39 1/2, 34, 30 1/3, 25 1/2, 21, 11.87, 11.29, 9.79, and 8.12 months. Subsequently, the algorithm was used to forecast monthly precipitation amounts for 10 years in advance of publication of the articles,[17,18] for 32 U.S. locations. An apparently similar algorithm was developed to predict monthly temperatures six years in advance of publication for 10 U.S. locations.[19]

An analysis of the correctness of these long-range forecasts based on Spear man's rank correlation coefficient[20] shows that about one half of the 384 correlations are positive, while one half are negative, leading one to believe that overall the forecasts are no better than random. While overall these forecasts may be random, the possibility does exist that the extremal forecasts might be more reliable than random. Accordingly, the years of highest and lowest precipitation were noted for each station and month, and the ranks observed for these maximal years were averaged. The observed ranks corresponding to the forecast minimums had a mean of 5.68 and a standard deviation of 2.93, while the observed ranks for the forecast maximums had a mean rank of 5.36 and a standard deviation of 2.87. Note that a random assignment of ranks would yield an average value of 5.5.

A similar analysis for the six years of forecast temperatures provided 120 rank correlations, 53 of which were negative and 67 of which were positive. The average ranks of the observed temperatures corresponding to the forecast minimum and maximums were both close to expected random value of 3.5. It would appear that these long-term forecasts of extreme events were not significantly correlated with reality.

Shorter-range forecasts than the preceding study are routinely published in U.S. newspapers, and examples can be found in Figure 4. The Weather Service long-range prediction group believes that these 30-day forecasts are useful and that they show some skill and have shown improvement over the years, with the caveat that these forecasts are not primarily intended for specific points, especially those that have local peculiarities of climate. However, the Weather Service does believe that these forecasts are suitable and useful for use on large geographical areas.[21]

The current 30-day forecasts classify temperature into three groups (upper 30 percent, middle 40 percent, and lower 30 percent), and precipitation into two groups (above or below the median). Prior to 1974 more numerous groupings were used, with temperatures being classified into five groups (1/8, 1/4, 1/4, 1/4, 1/8), and precipitation into three groups (1/3, 1/3, 1/3). Weather Service 30-day forecasts are referred to a 30-year base period called the “normal,” and the base period is intermittently updated to reflect a more recent “normal.”

It is instructive to consider these forecasts as they might be viewed by water-resource managers. On the Mohonk Trust lands are two small reservoirs used for water supply and irrigation, and it is conceivable that these reservoirs might be managed using the published 30-day forecasts for precipitation and temperature. For the period 1954–1973, the 30-day forecasts of precipitation were correct 39 percent of the time compared with the 36 percent correct that would have resulted from forecasting normal for each month. For the period January 1974 to April 1976, there were 28 monthly precipitation forecasts made on the basis of above or below the median. Twelve of these forecasts matched reality, that is, the later period precipitation forecasts were correct 42 percent of the time. For 30-day temperature forecasts during the period 1954–1973, the comparable values were 27 and 23 percent, while for the later-period temperatures 12 of 28 percent were correct, compared with the 11 of 28 percent that would have resulted from forecasting normal. There was no strong evidence for any seasonal or time bias in these results.

Larger-area evaluations of current monthly forecasts tend to be much more subjective and to yield results of even more dubious value to water-resource planners or managers. For example, consider that from October 1975 to February 1976 northern California experienced its worst drought since 1924, with many streams generating only 50 percent or less of their normal runoff.[22] The five monthly precipitation forecasts (Figure 4) for this region were, respectively,

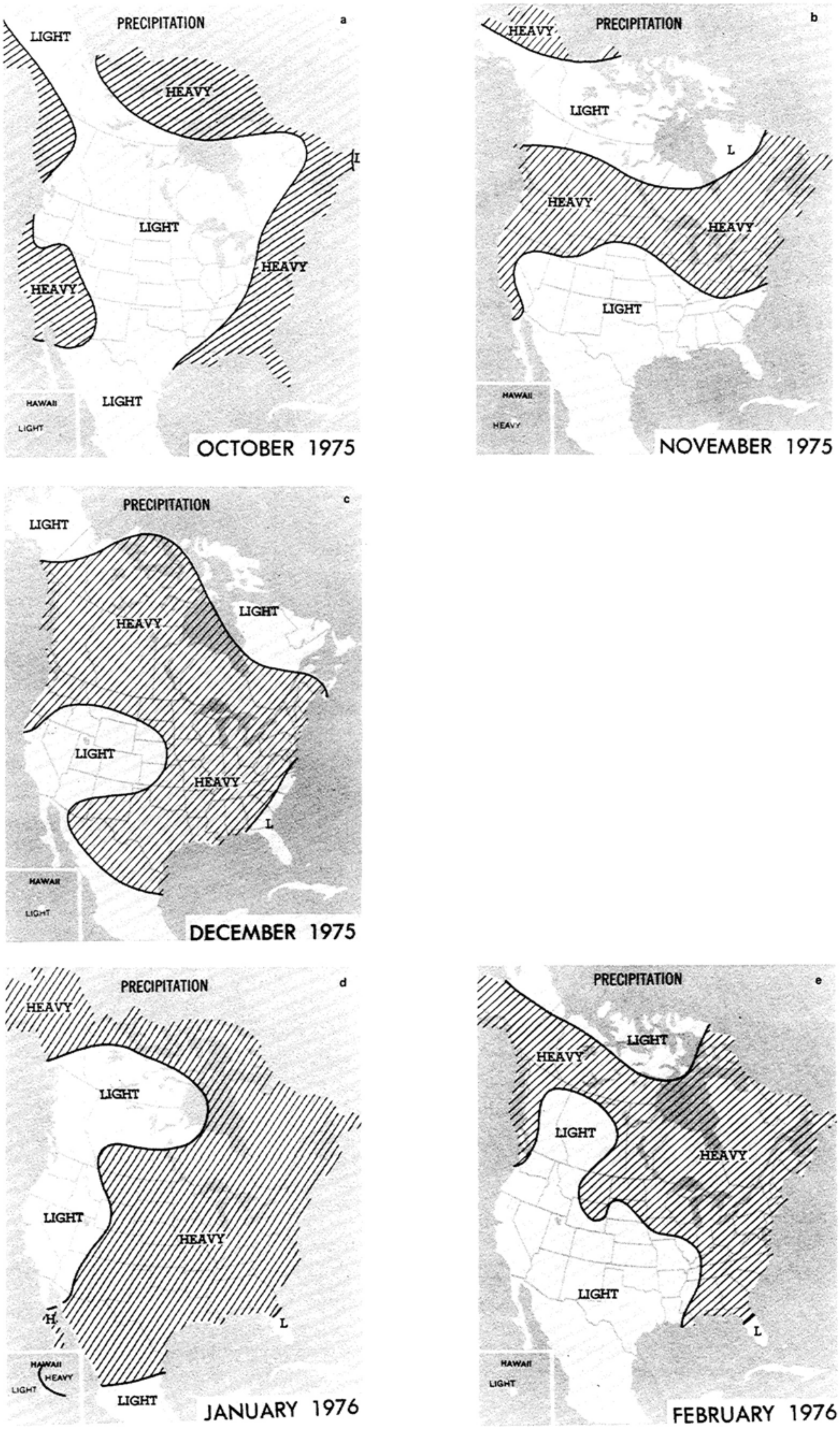

FIGURE 4 National Weather Service 30-day forecast of precipitation: (a) for October 1975; (b) for November 1975; (c) for December 1975; (d) for January 1976; (e) for February 1976.

above the median; above the median; some above, some below the median; below the median; below the median. It is difficult to see how such undiscerning statements could be operationally useful to hydrologic managers or planners. In addition, even if the transfer functions to variables of hydrologic interest were known and error-free, the forecasts for even large areas by waterresource standards could be very much in error. In a recent issue of *Western Water,* G. F. Snow reported that in February substantial rains fell in the area of California south of Merced, with parts of the San Joaquin valley receiving 200 percent of its normal February rainfall and parts of Southern California receiving up to 294 percent of the normal expected rainfall.[22] From Figure 4 (e) the comparable forecast for this location and period is seen to be “below the median.”

Other analyses of long-range forecasts, not reported here, support the general conclusion that past climatic forecasts have not been useful to the water-resource planning process. It would be an act of faith to assume that current long-range climatic forecasts are likely to be any more useful to water-resource planners than have past forecasts.

In summation, current long-range weather forecasts are optimistically only a little better than random. There is little or no verifiable scientific evidence to indicate that current long-range climatological forecasting is accurate and reliable to the point of being usable on the watershed or irrigation district basis that would be needed by those concerned with the operational management of water-resource systems. Further, given normal climatic variability and the customary 30-year lag between planning and operation of large water-resource systems, it appears unlikely that forecasts of climatic change will be relevant to the water-resource systems designer within the foreseeable future.

CLIMATIC CHANGE, DELIBERATE AND INADVERTENT

Leaders in climatology and economics are in agreement that a climatic change is taking place, and that it has already caused major economic problems throughout the world. ——CIA, 1974

The CIA report from which the above quote was extracted must surely rank as one of the most widely publicized and discussed documents in the history of climatology. That climatic change is taking place is almost tautological, for climatic change has been a property of the earth's atmosphere as long as the earth has had an atmosphere, and it seems probable that climatic change will continue even after mankind is no longer available to record the changes. What appears to separate this age from its precursors is that for the first time in history mankind has sufficient power to upset the world's climate or, at least, to trigger changes that might have occurred at a later date without mankind's modifications.

In this brief review only one inadvertent and one deliberate climatic modifcation will be discussed. Further details and possibilities are discussed in the paper by Schneider and Temkin and in the previously mentioned report of the *ad hoc* Panel on the Current Interglacial. The increasing use of fossil fuels in recent years has resulted in a global atmospheric CO_2 increase of about 0.7 percent per year.[23] CO_2 molecules are very strong absorbers of long-wave thermal radiation at wavelengths at which the earth's atmosphere is otherwise transparent. The increased absorption tends to insulate the earth's surface from infrared heat losses to outer space, leading to higher surface temperatures (the greenhouse effect). It has been estimated that a 10-percent increase in atmo spheric CO_2 is likely to warm the entire lower atmosphere by an average of about 0.3°C—an inadvertent climatic' change. Possible mechanisms for reconciling the apparent discrepancy between the decreasing temperature shown in Figure 3 and the expected increasing temperature of the greenhouse effect are to be found in the Schneider and Tempkin paper. Discussion of the probable importance of a climatic change of this magnitude to water-resource design can be found elsewhere in this report.

The one aspect of deliberate weather modification that concerns this panel is the suggestion that impregnating winter clouds with silver iodide crystals is a viable mechanism to augment the snowpack in the mountains of the arid West. It is evident that there are those with unshakable convictions who believe that the future water-supply shortages prognosticated by Dracup for the Upper Colorado River Basin can be avoided by the generation of extra snow whenever and wherever needed (note that integrated over time this would amount to deliberate climatic change). This group believes that existing technology and understanding are adequate for management purposes and that further research is either unnecessary or, if needed, should not be allowed to interfere with ongoing management programs—the public cannot continue to afford the luxury of further randomized tests. It is evident that there are others, just as determined in their beliefs, who conclude that snow augmentation is a most important area for an expanded program of carefully considered scientific research but that the existing knowledge and technology are inadequate to guarantee success and may even have effects contrary to those that are desired.

In an interesting program of ongoing research Farhar and her associates at the University of Colorado[24] have studied the sociology of those who favor management programs as opposed to those who favor further research into weather modification. Representatives of these two groups tend to come from quite different occupational and technical backgrounds, and it is easy to infer that our panel is unlikely to have contained representatives of either extremal group. It is true, however, that too many of our panel members have had experience in simulation and numerical analysis for the group as a whole to be regarded as a random sample.

It was not the duty of this panel to analyze and reanalyze weather-modification experiments, but we did conduct a literature review. The U.S. House of Representatives Subcommittee on the Environment and the Atmosphere has recently concluded hearings and published more than 1300 pages of testimony,[25] much of which is relevant to this subject and which in summation tends to support the view that more research is needed before seeding clouds on an operational basis with intent to increase snowfalls.

A prerequisite for any management program designed to modify a geophysical process, be it snow augmentation, earthquake attenuation, or the subsidence of Venice, is accurate forecasts of the relevant phenomena and all major side effects, based on three-dimensional, time-varying, physics-based, computer models. The snow augmentation movement is not supported in this manner, and scientific credibility for a management program is lost.

Further, the statistical justification for snow-augmentation management programs is weak because the statistically randomized portions of snow-augmentation experiments have not shown consistent results (positive, negative, and inconclusive results abound). Claims for success have been based on *post hoc* analyses in which certain storms and measurement stations have been removed from the analyses—a procedure that is perfectly honest and permissible providing the objective is increased understanding of the phenomena being studied, better simulation models, or more carefully designed future experi ments. *Post hoc* statistical analyses do not, however, amount to controlled, unbiased statistical tests[26] of the phenomena being studied and are not a justification for management programs, only for further research.

It is the opinion of this panel that weather-modification technology has the potential to be a useful tool for increasing the resilience of water-resource systems, although more research will be needed before this hypothesis is proven (see the following section on Climatic Transfer Functions). Furthermore, to justify future water-resource projects on the grounds that current weathermodification technology will produce the water as needed appears somewhat unreasonable.

CLIMATIC TRANSFER FUNCTIONS

Before the forecast values of future changed climates become useful to hydrologists and water-resource planners, the variables of the climatic forecast have to be converted into the variables of water supply and projected water use. Water-resource designers customarily work with seasonal water-supply values, where the number of seasons varies from 2 to 12 per year. However, for some situations, annual flow estimates are sufficient, while for other situations very-short-period (daily) estimates are required.

Hydrologists have generated hundreds of models for converting climatic variables into estimates of streamflow, but it is only recently that hydrologists have started to make the necessary sensitivity tests[27] on the physics-based models, and only one attempt at an unbiased statistical evaluation of model forecasts has been reported.[28] This latter study, conducted by the World Meteorological Organization (WMO) from 1968 to 1974, evaluated the performance often models on up to six watersheds for a two-year forecast period. The results were scarcely encouraging to the model builders. Even with the actual daily rainfall and temperature measurements recorded within the individual basins for the forecast periods, the forecast flows were often greatly in error. Errors in the sum of the forecast flows for the complete two-year forecast periods ranged in excess of 40 percent (see Figure 5 for an example). Furthermore, as shown in Figure 6, individual events sometimes showed little or no correlation between the observed and forecast values. It is possible to conclude from the WMO study that existing hydrologic models may be poorly adapted to the job of mapping forecast values of climatic variables into water-supply forecasts. In addition, snowmelt routines that could be used to convert augmented snow

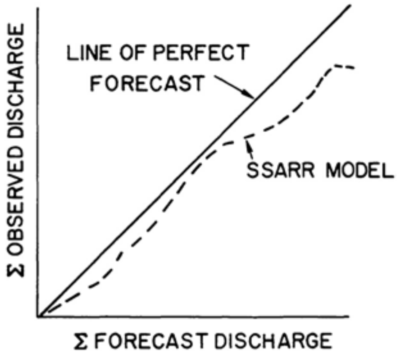

FIGURE 5 Plot of cumulative forecast for a two-year period against cumulative observed flow for the Nam Mune River. Figure redrawn from WMO Hydrology Report No. 7, 1974.

pack figures to water behind the dam were not included in the WMO analysis. Clearly, such a relationship is nonlinear in both time and space, and the models used to estimate this transfer function need to be evaluated in an unbiased and careful manner before the water results of snow augmentation can be known.

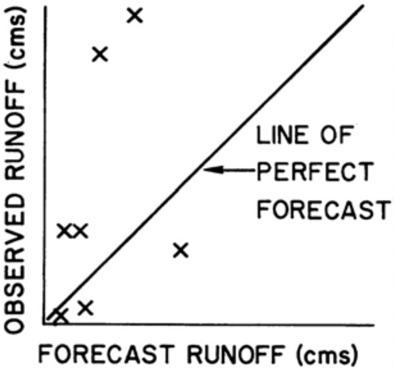

FIGURE 6 Plot of the highest daily flow per month forecast for a two-year period against the comparable observed flows. Appreciable rainfall occurred in only 7 of the 24 months (SRFCH model, Wollombi Brook data). Figure redrawn from WMO Hydrology Report No. 7, 1974.

The WMO study has shown that our existing climate–water transfer functions are inaccurate, but Matalas and Fiering point out that further general uncertainties will accrue when these models are used to forecast under a new uncalibrated climatic regime. Changes in temperature and precipitation regimes cause changes in cloud cover and radiation transfer, which can initiate changes in the patterns of human settlement, cropping, and development. In turn, these changes can cause changes in streamflow patterns, which can cause further geomorphological changes. These latter changes are themselves affected by the extent to which regional flora and fauna become adapted to the new climatic regimes. In summation, transfer functions to get from a climatic forecast to water-resource design variable, *Cf*, are in a very primitive stage of development and need to be greatly strengthened before they achieve statistical reliability.

In addition, it is possible that the specific forecasts of climatic variables may themselves be in error and that the combination of errors in the initial forecasts, combined with the errors in the climate-to-water-supply conversion, may lead to the transfer of negative information.[29] That is, the water-resource designer might be able to obtain a better design by considering only the existing record and its variability while ignoring the forecast values. Much careful research will be needed before such questions are satisfactorily resolved.

Besides the climate-to-water-supply conversion discussed above, the water-resource planner may want to consider that the demands for water under a forecast climate may be different from the currently observed one. For instance, how much water for energy or irrigation will be needed under the new climate regime? What crops should be grown and where? How will the cropping patterns and irrigation demands vary in the future? In their paper, Lofting and Davis discuss the difficulties that economists have in defining, projecting, and estimating water demand.

THE ECONOMIC PROBLEM OF PREDICTING FUTURE WATER DEMAND

Economic uncertainties have been shown under certain circumstances to be more important to water-resource design than uncertainties that arise from hydrologic causes. Lofting and Davis document the problems facing those who must estimate water “demand,” and they point out that the uncertainties in the economics (hence, the economic benefits accruing to a possible water-resource design) appear to be increasing rather than decreasing. Further, they note that those who wish to apply classical market economics find many special problems attached to estimating future water demand. For instance, demand for water does not exist in a conventional sense until after the supply has been assured, then “use” expands in the area up to the limits of the available supply but not beyond. Thus, present use is a self-fulfilling prophecy of a previous estimate of a potential demand and may be misleading as a basis for estimating future “requirements.” There are also problems associated with the concept of water use as an elastic property of price, a concept that, for water, may or may not be true. In addition, there are special difficulties attached to the manner in which the statistics and basic data of water use are estimated and recorded. The Lofting and Davis paper makes interesting reading for those who are concerned with future water requirements and our ability to estimate them. Their paper also includes practical proposals for research, which if conducted would go a long way toward reducing these more obvious uncertainties in the economics of estimating future water use.

But, as Lofting and Davis note, there are at least three new sources of economic uncertainty that make forecasts of future water demands particularly uncertain. The first cause of major new uncertainties in forecasting future water demands is the enactment of Public Law 92-500, which has legislated the elimination of the discharge of all pollutants by 1985 and the regulation of all irrigation to assure minimal water use and minimal return discharge. A major present use of water is pollution abatement by dilution, and if the law and its timetable are enforced, there will be revolutionary changes in future water demands. Water economists are only just beginning to assess all the implications and ramifications of Public Law 92-500.

The second source of new uncertainty in the forecast of future water demands is less certain of execution but could also cause large changes in future water usage, namely, a large increase in irrigated agriculture. The Malthusian day of reckoning appears to be rapidly approaching, with world food supplies low and world population still increasing at a much greater rate than world food supplies. It has been suggested that the food deficits of “Third World” countries could be met by expansion of the agricultural production of the United States. To meet this goal might entail, among other things, an increase in irrigated agriculture and perhaps the resurrection of some dormant plans for the interbasin transfer of water. Whether the United States has the political cohesion or the economic power to succeed in such a policy was not a subject of investigation for this panel, but the possibility of such a national goal increases uncertainties in estimates of water demand.

The third new cause of increased economic uncertainty in the estimates of future water supply is the threat of climatic change, real or imagined, which can alter what farmers will plant, as well as what economists think they will plant. At present, we do not know whether climatic change will result in more or less water available for storage behind a proposed dam. Further, we do not know what the net effect of a postulated average annual global temperature change may be on the future water requirements within an actual specific project area. It would appear that rather than global averages, the climatic-change estimates that might actually influence projections of water use are estimates of changes in frequency and severity of extremal periods. Climatologists may find reliable, nonstationary, extreme value forecasting beyond their ability.[30]

THE SOCIETAL IMPACT OF WATER SHORTAGES

A good rain is the only quick solution to problem of drought. . . . Unfortunately, a good rain washes away more than the drought, it washes away much of man's interest in providing for the next one, and it washes the supports from under those who know that another dry cycle is coming and who urge their fellows to make ready for it.

——W. P. Webb, 1954

From reading Meier's contribution to this volume, one can find that what was true in Texas in 1954 is still true over most of the United States in 1977. Nearly all the thousands of individual water-resource source systems currently operating in this country are susceptible to shortages of various severity and duration. Shortages can come from inadequate supplies, structural failures, increased demand, or poor operating policies. The one common denominator to link all of these future failures as they occur is that their effects will be made more noticeable by a lack of advanced “contingency planning” and by the slowness with which the responsible officials can be expected to act.

As Matalas and Fiering note, system resiliency is a fertile field for further water research, and Meier's “societal impacts” are an aspect of resiliency that should not be overlooked. Resiliency research can be expected to aid greatly in the production of sound contingency plans and even to contribute to better estimates of water demand. If climatic change were sudden and pronounced and in a direction that greatly reduced supply or increased demand, then the need for such research would become immediately obvious, but the need exists even without considering possible climatic changes.

WATER LAW AND CLIMATIC CHANGE

If our climate should change for the worse, our water laws should change for the better.

——Trelease, 1976

The one area of the climatic change-water supply problem that has not yet been mentioned in this introduction is the matter of water law. Elsewhere in this volume Trelease uses an eloquent broad brush to discuss the major aspects of U.S. water law from the point of view of climatic change, He stresses that water law can and does change as a result of man's perception of his aqueous environment and that legal changes can be expected to accelerate under the stress of climatically induced change. Trelease believes that future legal changes will tend to generate increased flexibility in rights and institutions, and, optimistically, all of this wil lead to the greater good for the greater number—an encouraging prospect.

However, water law is complicated and varies widely from state to state, as well as from river to river. In the eastern states, vestiges of English common law, in the form of “riparian” rights, still remain, although often overlain by regulatory statutes and federal controls. Litigation is still a major method used to allocate water supplies in the east, and this approach to conflict resolution would appear to be unnecessarily costly, slow, and clumsy. Trelease has many practical suggestions for making water law more responsive to human needs and desires, but he also places “prior appropriation,” “interstate compacts,” “reserved rights,” and “environmental water law” in their appropriate context, both historically and with regard to future climatic change.

CONTRASTING PROBLEM AREAS—THE NORTHEAST AND THE SOUTHWEST

Early in the panel's deliberations it was decided that the exercise should not be wholly academic and that the panel should try to assess the climatic change–

water supply function for at least two sample areas. Schwarz agreed to consider the metropolitan industrial northeast, and John Dracup volunteered to make one more assessment of the much studied Colorado River Basin.

The northeast contains about 5 percent of the nation's land area, but it holds about 25 percent of its population and produces nearly 30 percent of its wealth. Some 1200 water suppliers in the region currently furnish an average 241 m^3/sec of water, with 70 percent of this supply being used in the three metropolitan areas of Washington, New York, and southeastern New England. Depending on which projection of growth is realized, the region is likely to require 416–478 m^3/sec of assured supply by the year 2000.

Given that all major water-supply projects in the northeast have been stalled for more than 10 years over uncertainties in the individual demand forecasts, as well as because of fiscal and environmental constraints, it would appear that water shortages in the northeast are going to be prevalent in the near future. The alternatives to severe water shortages in the northeast appear to be either climatic changes that prevent shortages in supply in a consistent beneficial manner or a much slower regional growth rate than has been projected. The first of the above alternatives is questionable, and the second may be politically undesirable. Schwarz suggests detailed measures that could alleviate some of these threatened water shortages, but it would appear that without major new regional cooperation, and federal commitment, the northeast will soon suffer water shortages.

Dracup discusses the Colorado compact that divides the 1924 estimate of long-term flow equally between the Upper and Lower Basin states. He notes that legal constraints require specified releases from the upper to the lower basin states, that the existing water-storage configuration favors the lower basin states, and that extensive energy developments projected for the Upper Basin states entail extensive water requirements. His conclusion is that the results of any period of extended low flow would oppress the Upper Basin states more than the Lower Basin states and that water shortages in the Upper Basin states can be expected after 1985, if not sooner.

When consumptive use in the Upper Basin states becomes hampered by the Colorado compact allocation of flow, it seems probable that the Upper Basin states will attempt to renegotiate the contract. At that juncture, the courts or Congress will have to clarify whether the intent of the compact was to divide the long-term flow equally between upper and lower basin states or to guarantee 75 maf of water per decade to the Lower Basin states. Current estimates of the long-term flow indicate that these two interpretations of the compact are conflicting. However, given that approximately four years of average flow can be stored near the compact point, it would be possible to adjudicate future dry-period releases based on the previous year's adjusted virgin flow and hence to bypass further consideration of climatic change or the unknowable true long-term mean flow of the river—a flexible solution to match a variable climate.

SUMMARY

The nation as a whole can expect to experience severe local and even regional water shortages. Future water shortages may be exacerbated by climatic change, but current and foreseeable climatologic forecast ability is not likely to be accurate or specific enough in either time or space to be useful to the water-resource planner. However, there are many useful measures that could be implemented now that would help to mitigate the undesirable effects of future water shortages.

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$$\bar{X} = \frac{1}{T}\sum_{i=1}^{T} x_i ; \qquad S = \sqrt{\frac{1}{T}\sum_{i=1}^{T} x_i^2 - \bar{X}^2}.$$

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20. The Spearman rank correlation coefficient is defined as

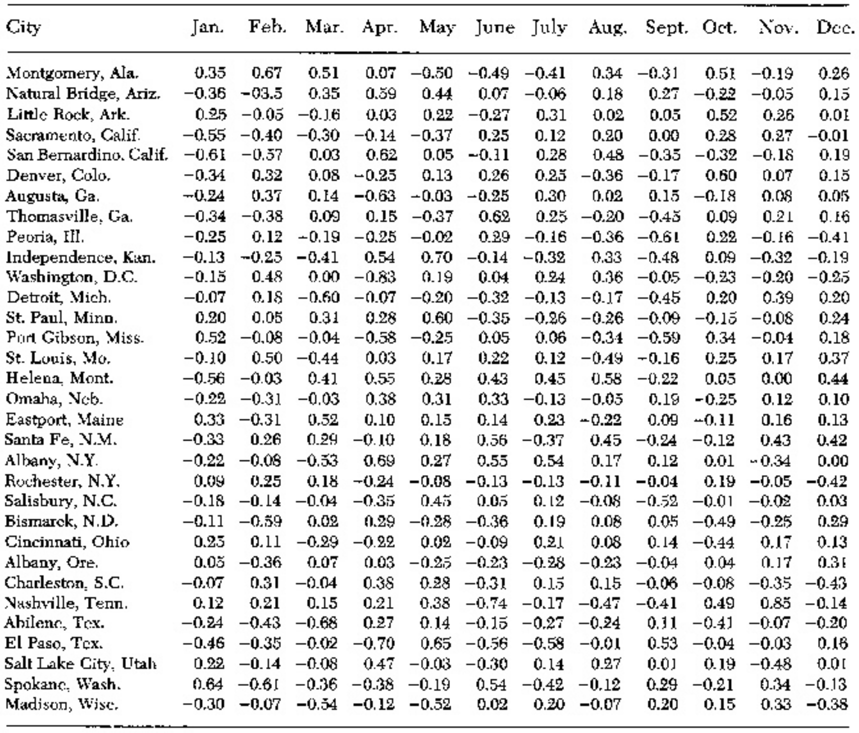
$$1 - \frac{6\sum_{i=1}^{N} d_i^2}{N^3 - N},$$

where *N* is the number of values to be ranked and *d* is the difference in the individual rankings. For January precipitation at Montgomery, Ala., from 1961 to 1970 the values and ranks of the 10 forecasts and 10 observed precipitation amounts were:

Year		1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
Forecast		+52	−9	+3	+12	+8	+40	−10	−41	−37	−48
Ranked Forecast		10	5	6	8	7	9	4	2	3	1
Observed		2.18	5.20	7.14	6.49	6.10	6.20	2.77	2.78	1.85	2.83
Ranked Observation		2	6	10	9	7	8	3	4	1	5
yielding *d* and d^2 values of	*d*	8	−1	−4	−1	0	1	1	−2	2	−4
	d^2	64	1	16	1	0	1	1	4	4	16

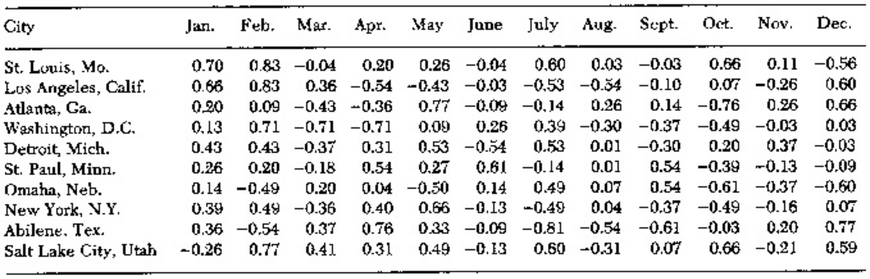
and a Spearman rank correlation coefficient of +0.35. A value of +1.0 would signify perfect agreement between forecast and observed ranks, while a value of −1.0 would signify a complete disagreement. Equal values in the observations on values in the forecasts were treated following Siegel's *Non-Parametric Statistics,* McGraw-Hill Book Co., New York, 1956. Data for the complete analysis are presented in Tables R.1 and R.2.

TABLE R.1 Rank Correlations between Forecast and Observed Precipitation for the Period 1961–1970



City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Montgomery, Ala.	0.35	0.67	0.51	0.07	−0.50	−0.49	−0.41	0.34	−0.31	0.51	−0.19	0.26
Natural Bridge, Ariz.	−0.36	−03.5	0.35	0.59	0.44	0.07	−0.06	0.18	0.27	−0.22	−0.05	0.15
Little Rock, Ark.	0.25	−0.05	−0.16	0.03	0.22	−0.27	0.31	0.02	0.05	0.52	0.26	0.01
Sacramento, Calif.	−0.55	−0.40	−0.30	−0.14	−0.37	0.25	0.12	0.20	0.00	0.28	0.27	−0.01
San Bernardino, Calif.	−0.61	−0.57	0.03	0.62	0.05	−0.11	0.28	0.48	−0.35	−0.32	−0.18	0.19
Denver, Colo.	−0.34	0.32	0.08	−0.25	0.13	0.26	0.25	−0.36	−0.17	0.60	0.07	0.15
Augusta, Ga.	−0.24	0.37	0.14	−0.63	−0.03	−0.25	0.30	0.02	0.15	−0.18	0.08	0.05
Thomasville, Ga.	−0.34	−0.38	0.09	0.15	−0.37	0.62	0.25	−0.20	−0.45	0.09	0.21	0.16
Peoria, Ill.	−0.25	0.12	−0.19	−0.25	−0.02	0.29	−0.16	−0.36	−0.61	0.22	−0.16	−0.41
Independence, Kan.	−0.13	−0.25	−0.41	0.54	0.70	−0.14	−0.32	0.33	−0.48	0.09	−0.32	−0.19
Washington, D.C.	−0.15	0.48	0.00	−0.83	0.19	0.04	0.24	0.36	−0.05	−0.23	−0.20	−0.25
Detroit, Mich.	−0.07	0.18	−0.60	−0.07	−0.20	−0.32	−0.13	−0.17	−0.45	0.20	0.39	0.20
St. Paul, Minn.	0.20	0.05	0.31	0.28	0.60	−0.35	−0.26	−0.26	−0.09	−0.15	−0.08	0.24
Port Gibson, Miss.	0.52	−0.08	−0.04	−0.58	−0.25	0.05	0.06	−0.34	−0.59	0.34	−0.04	0.18
St. Louis, Mo.	−0.10	0.50	−0.44	0.03	0.17	0.22	0.12	−0.49	−0.16	0.25	0.17	0.37
Helena, Mont.	−0.56	−0.03	0.41	0.55	0.28	0.43	0.45	0.58	−0.22	0.05	0.00	0.44
Omaha, Neb.	−0.22	−0.31	−0.03	0.38	0.31	0.33	−0.13	−0.05	0.19	−0.25	0.12	0.10
Eastport, Maine	0.33	−0.31	0.52	0.10	0.15	0.14	0.23	−0.22	0.09	−0.11	0.16	0.13
Santa Fe, N.M.	−0.33	0.26	0.29	−0.10	0.18	0.56	−0.37	0.45	−0.24	−0.12	0.43	0.42
Albany, N.Y.	−0.22	−0.08	−0.53	0.69	0.27	0.55	0.54	0.17	0.12	0.01	−0.34	0.00
Rochester, N.Y.	0.09	0.25	0.18	−0.24	−0.08	−0.13	−0.13	−0.11	−0.04	0.19	−0.05	−0.42
Salisbury, N.C.	−0.18	−0.14	−0.04	−0.35	0.45	0.05	0.12	−0.08	−0.52	−0.01	−0.02	0.03
Bismarck, N.D.	−0.11	−0.59	0.02	0.29	−0.28	−0.36	0.19	0.08	0.05	−0.49	−0.25	0.29
Cincinnati, Ohio	0.23	0.11	−0.29	−0.22	0.02	−0.09	0.21	0.08	0.14	−0.44	0.17	0.13
Albany, Ore.	0.05	−0.36	0.07	0.03	−0.25	−0.23	−0.28	−0.23	−0.04	0.04	0.17	0.31
Charleston, S.C.	−0.07	0.31	−0.04	0.38	0.28	−0.31	0.15	0.15	−0.06	−0.08	−0.35	−0.43
Nashville, Tenn.	0.12	0.21	0.15	0.21	0.38	−0.74	−0.17	−0.47	−0.41	0.49	0.85	−0.14
Abilene, Tex.	−0.24	−0.43	−0.68	0.27	0.14	−0.15	−0.27	−0.24	0.11	−0.41	−0.07	−0.20
El Paso, Tex.	−0.46	−0.35	−0.02	−0.70	0.65	−0.56	−0.58	−0.01	0.53	−0.04	−0.03	0.16
Salt Lake City, Utah	0.22	−0.14	−0.08	0.47	−0.03	−0.30	0.14	0.27	0.01	0.19	−0.48	0.01
Spokane, Wash.	0.64	−0.61	−0.36	−0.38	−0.19	0.54	−0.42	−0.12	0.29	−0.21	0.34	−0.13
Madison, Wisc.	−0.30	−0.07	−0.54	−0.12	−0.52	0.02	0.20	−0.07	0.20	0.15	0.33	−0.38

TABLE R.2 Rank Correlation between Forecast and Observed Temperature for the Period 1962–1967



City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
St. Louis, Mo.	0.70	0.83	−0.04	0.20	0.26	−0.04	0.60	0.03	−0.03	0.66	0.11	−0.56
Los Angeles, Calif.	0.66	0.83	0.36	−0.54	−0.43	−0.03	−0.53	−0.54	−0.10	0.07	−0.26	0.60
Atlanta, Ga.	0.20	0.09	−0.43	−0.36	0.77	−0.09	−0.14	0.26	0.14	−0.76	0.26	0.66
Washington, D.C.	0.13	0.71	−0.71	−0.71	0.09	0.26	0.39	−0.30	−0.37	−0.49	−0.03	0.03
Detroit, Mich.	0.43	0.43	−0.37	0.31	0.53	−0.54	0.53	0.01	−0.30	0.20	0.37	−0.03
St. Paul, Minn.	0.26	0.20	−0.18	0.54	0.27	0.61	−0.14	0.01	0.54	−0.39	−0.13	−0.09
Omaha, Neb.	0.14	−0.49	0.20	0.04	−0.50	0.14	0.49	0.07	0.54	−0.61	−0.37	−0.60
New York, N.Y.	0.39	0.49	−0.36	0.40	0.66	−0.13	−0.49	0.04	−0.37	−0.49	−0.16	0.07
Abilene, Tex.	0.36	−0.54	0.37	0.76	0.33	−0.09	−0.81	−0.54	−0.61	−0.03	0.20	0.77
Salt Lake City, Utah	−0.26	0.77	0.41	0.31	0.49	−0.13	0.60	−0.31	0.07	0.66	−0.21	0.59

21. U.S. Department of Commerce (1961). Verification of the Weather Bureau's 30-day outlooks, Tech. Paper No. 39. It should be noted that the issuers of these forecasts prefer to refer to them as outlooks—a semantic difference not a functional one. The analysis of the Mohonk data presented here tends to give a lower estimate of forecast reliability than did the in-house evaluation because different criteria and periods were used in the evaluations. A more interest

ing criterion than used in either of these evaluations would be one based on the initial 5-day period forecast. Five days is the limit for skillful synoptic weather forecasting, and what is of interest is the forecast skill that exists beyond this initial period.

22. *Western Water* (March–April 1976). Published by the Association of California Water Agencies.

23. C. D. Keeling, J. A. Adams, C. A. Ekdahl, and P. R. Guenther (1976). Atmospheric carbon dioxide variations at the South Pole, *Tellus 28,* 552.

24. B. C. Farhar, Human Ecology Research Services, 855 Broadway, Boulder, Colo. 80302.

25. Publications Nos. 78 and 79, Committee on Science and Technology, U.S. House of Representatives, Ninety-fourth Congress, Second Session, 1976.

26. Even before statistical tests and statisticians were in vogue, the dangers *of post hoc* data analysis with a single hypothesis in mind (silver iodide increases snowpacks) were appreciated by some. In this regard, see H. C. Chamberlin (1890). *Science 15,* 92, reprinted in *Science 148* (1965), from which the following quote was gleaned:

> There is an unconscious selection and magnifying of the phenomena that fall into harmony with the theory and support it, and an unconscious neglect of those that fail of coincidence. The mind lingers with pleasure upon the facts that fall happily into the embrace of the theory, and feels a natural coldness toward those that seem refractory. Instinctively there is a special searching-out of phenomena that support it, for the mind is led by its desires. There springs up, also, an unconscious pressing of the theory to make it fit the facts, and a pressing of the facts to make them fit the theory.

The panel has not determined whether such unconscious biasing exists in the *post hoc* snow augmentation analyses, but it does wish to point out that the danger exists and that independent scientific corroboration of any *post hoc* analysis is desirable from a research standpoint and absolutely necessary before implementing a management program.

27. R. A. Freeze (1975). A stochastic-conceptual analysis of one-dimensional groundwater flow in non-uniform homogeneous media, *Water Resources Res. 11,* 5.

28. Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting, World Meteorological Organization, Operational Hydrology Rep. No. 7 (1974).

The project involved the testing of ten operational conceptual hydrologic models submitted by seven countries on six standard river catchment data sets from climatologically and geographically varied conditions in six countries. Each data set consisted of two distinct periods: a calibration period (six years) and a verification period (the next two years). For each data set, the model owners were supplied with the necessary concurrent observed input data (precipitation, evaporation, and other meteorological data) and observed output data (streamflow) for the six-year calibration period and only the observed input data for the two-year verification period. The observed output data for the two-year verification period were retained by the WMO Secretariat.

For each data set, the model owners used the concurrent observed input and output data for the six-year calibration period to calibrate and develop the parameters of their models and employed the additional two years of observed input data in the verification period to produce a simulated discharge (computed output). The simulated discharges produced by the tested models for both the calibration and verification periods in each data set were then centrally evaluated and compared by WMO using several graphical and numerical verification criteria agreed upon by all modelers.

29. J. R. Wallis and N. C. Matalas (1972). Information Transfer via Regression in Markovian Worlds, IBM Research, Yorktown Heights, N.Y., RC 4207.

30. In this regard consider the much quoted statement, ". . . the probability of getting fifteen consecutive years that good is about one in 10,000" (referring to the unusually good weather for agriculture in the United States from 1957 to 1972). The uncertainties that should be attached to a transfer function that converts a paleoclimatic index variable to a prairie wheat yield are totally unknown. However, they may be sufficiently large that the above authoritative sounding probability statement may well be just another example of a type II imaginary number (see *Time,* Aug. 2, 1971, for other examples of this phenomenon).

I CLIMATOLOGY

1

Water Supply and the Future Climate

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WHAT IS CLIMATIC CHANGE?

This chapter addresses a variety of questions related to issues of understanding the climate and how it might change and, additionally, how climate is related to the water supply. Many conflicting aspects of climate have recently been discussed in the news. One hears about approaching ice ages on the one hand and the melting of the ice caps on the other with both natural and human-induced postulated causes. For example, Reid Bryson (in Alexander, 1974) has said that “there is very important climate change going on right now, and if the trend continues, will affect the whole human occupation of the earth—like a half billion people starving.” On the other hand, former U.S. Secretary of Agriculture Earl Butz has been quoted to the effect that such statements are at best without scientific bases and are at worst apocalyptic nonsense. Obviously, there is much confusion on the issue. Although the following discussion may add little to reduce the uncertainties, it is an attempt to show the range of arguments used, with a further attempt to tie the issues to questions of water supply in order that one may gain a feeling for the types of uncertainties that decision makers may have to face in the future.

Figure 1.1 shows some long-term temperature records extracted from ocean-sediment cores over the last 700,000 years (Emiliani, 1972).

There remains considerable dispute about the magnitude of the temperature fluctuations, which are on the order of 5°C, but the figure does, nonetheless, show an important point: over this several-hundred-thousand-year period there were fairly large excursions in temperature, with the cold and warm periods known as glacials and interglacials, respectively, these being separated in time by some 10,000 to 100,000 years. From a statistician's point of view, this record might appear to resemble a stationary time series. However, from the perspective of a human lifetime, or for that matter all of human history, the record contains dramatic climatic changes. Hence one may raise the question: “What is climatic change?” In reply, it should be stated that climate is a time average of the instantaneous state of atmosphere (i.e., the weather events) and that the weather itself is unpredictable in detail past a few weeks (see GARP, 1975, for a review).

Some people, in fact, believe it to be unpredictable in practice after only a few days, but it is theoretically possible that some skill of weather prediction exists up to the period of a few weeks. The atmosphere scrambles itself to a point where there is practically no recognition of its initial condition after some two to four weeks. Therefore, any climatic average that one takes that is longer than that predictability period is in essence averaging a fluctuating time series of unpredictable weather events. Does this mean that there can be no climatic predictability a month or a season or a decade ahead? The answer is clearly *"yes"* for weather but maybe "no" for climate, since there is no established theoretical reason why a time average of weather must also be unpredictable. From this average one would not be able to predict, for example, on what day in the next month and where a storm is going to take place; but one might be able to predict a few months into the future the number of storms that may pass through a given region in a given time. This latter possibility still remains theoretically conceivable with above-zero probability.

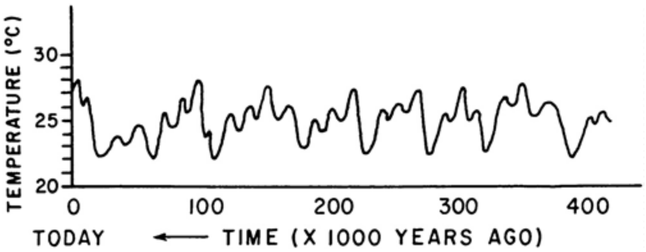

FIGURE 1.1 Long-term temperature trends extracted from ocean sediment cores (after Emiliani, 1972).

In 1974, at the Global Atmospheric Research Program Conference on Climate Modeling (held in Stockholm), a large number of experts attempted to set up a plan for future climate research (GARP, 1975). On the first day of the conference, about a dozen modelers, who were mainly interested in discussing questions about parameterizing their models and deciding what physical theories and observations were needed for their verification, decided that in the first half hour they would dispose of the issue of a definition of climate. Hours later they were still working on this definition. Essentially, the definition began from the obvious fact that climate is just a time average of weather. However, this being rather imprecise implied the need for some subdefinitions, e.g., the "climatic time series," which was defined as the time series of some fluctuating climatic parameter, say, rainfall. A "climatic sample" was also defined. It is the length of time over which one computes statistics for that time series. The "climate" is simply the statistical properties of the climatic time series taken over a specified sample period. When one takes two climatic samples and finds that they are different, "climatic change" is further defined. One still needs to investigate the statistical significance of those differences. That is, one must ask: Does the difference in the climate of the two samples occur because of unpredictable fluctuating components, e.g., the daily weather, or because of changes in the long-time statistics (or an ensemble mean) traceable to some varying physical forcing mechanism, e.g., usually a boundary forcing factor such as a volcanic dust veil?

From the above it is clear that in studying climatic change the length of the averaging period and the size of the averaging region are quite important. In fact, the physical processes that are most influential on the short time scales could well be different from those that operate on the long ones. Thus, a result of the Stockholm meeting (as seen from the participants' lengthy attempt to define climate) is that anyone referring to "climate" should be certain that the sample length is more than three weeks (which is more than the period of weather predictability) and that extreme care should be used in specifying the averaging period and statistical procedure. It is important that precision be used in the specification of the definition of climate. In the remainder of this paper, samples and averages will be considered for much shorter terms than ice ages and for periods longer than three weeks.

Figure 1.2 shows that the climate fluctuates on all time scales (U.S. Committee for the Global Atmospheric Re

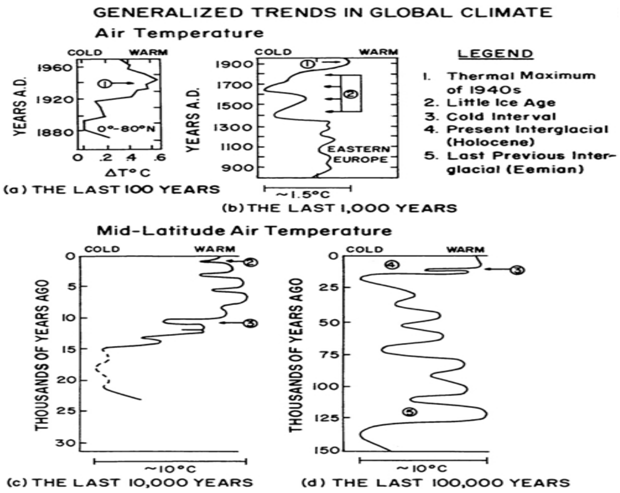

FIGURE 1.2 Generalized trends in global climate represented by approximate surface-temperature patterns that prevailed over a variety of time scales for the past 150,000 years.

search Program, 1975). In the past 1000 years, temperature has fluctuated on the order of 1 1/2°C. This may seem to be of minimal magnitude, but, from Figure 1.1, it is recalled that the magnitude of the glacial to interglacial oscillation was only about 5°C globally, although actually many times this at the high latitudes (Matthews *et al.*, 1971). The cool period in Figure 1.2 (b) between about 1400 and 1800 is known as the Little Ice Age in Europe and shows a decrease in temperature of only about 1°C. A change of this magnitude for food crops can be put in perspective when one notes that with a couple of degrees movement northward in latitude through the central part of the United States one would find that a 10-day drop in growing season is matched roughly by a 1°C drop in average temperature. The implication here is that a large-scale areal change in temperature of some 1°C is not necessarily trivial for people. Finally, the recent record [Figure 1 (a)] shows a hemispheric warming of about half a degree to 1940, followed by a cooling. Again a problem exists with this record in that it is really an estimate of a hemispheric average. Even though it is based on instrumental observations taken at many points, there still remain large areas left uncounted or uncovered by measurements. When referring to it as a hemispheric average, sampling error bars on the order of tenths of a degree should probably be placed on this record. It is clear then that difficulties exist even in pinning down past climatic changes to a very high degree of accuracy. It has also been mentioned that human societies are vulnerable to small changes in the climatic system and that a hemispheric temperature change of only a few degrees, or even perhaps tenths of a degree, can be important.

PHYSICAL FACTORS CAUSING CLIMATIC CHANGE

Figure 1.3 (from Schneider and Mesirow, 1976) contains a very simple overview of the mechanisms that drive our climate. The straight arrows represent the energy coming from the sun, of which annually about 30 percent is reflected (the reflectivity is called the earth's albedo). The wavy arrows represent the outgoing planetary infrared radiation. It is well known that the tropics are warm because they receive more heat from the sun than they emit as infrared radiation, and the poles are cold because of a greater average solar zenith angle and the presence of more highly reflective ice- and snow-covered surfaces. Thus in a simple picture the warm air rises in the tropics and moves poleward. As the air rises, it takes with it the fast rotational speed of the equator, which provides the momentum that creates the westerly winds in the mid-latitudes. Because the circulation is driven by the equator-to-pole *temperature difference,* the system is much more vigorous in the winter hemisphere than in the summer hemisphere.

This equator-to-pole temperature difference driven circulation is quite important, since a variation in global mean temperature is usually amplified at the poles. For example, from Figure 3.6 of Matthews *et al.* (1971), it is seen that the major recent temperature change (in the northern hemisphere at least) occurred in the higher latitudes. Some theoretical studies (e.g., Manabe and Wetherald, 1975) also suggest that a change in global temperature from changed surface heating will be amplified at the poles and thus will result in a change in the equator-to-pole temperature gradient. Since the circulation systems depend on this gradient, a seemingly small change in global temperature may thus latitudinally shift the average location of the circulation systems. Based on both some theoretical considerations and observations, Bryson (1974) argues that if the north polar region cools more than the equatorial region, the Asian and African monsoon belts get compressed, that is, they would move slightly equatorward, and the midlatitude baroclinic zones, the westerly belts, would also move toward the equator. Comparable evidence (e.g., Kellogg, 1977) exists suggesting from reconstructions of climatic warm periods that the opposite occurs when the poles warm more than the equator. This hypothesis is beginning to appear to have some theoretical support, since some recent numerical modeling experiments also show a temperature gradient monsoon effect. For example, Gates (1976) and Williams *et al.* (1974) have shown with numerical simulations that during the last (Wisconsin) ice age, the monsoon rains were weakened in their simulations. Nevertheless, the connection between circulation regimes and equator-to-pole surface-temperature gradient is still based on fragmentary evidence and thus remains somewhat controversial and qualitative.

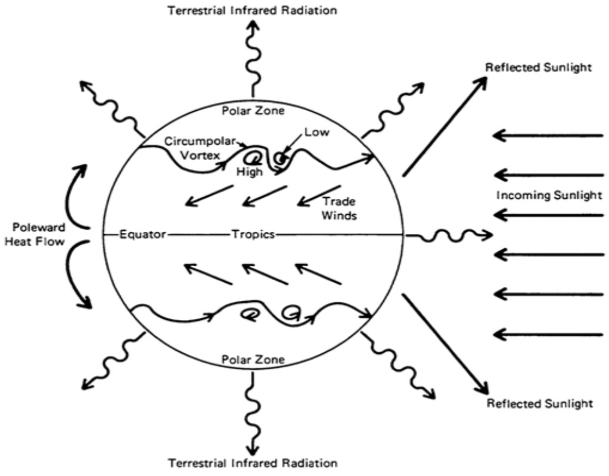

FIGURE 1.3 Schematic illustration of how the major weather systems of the earth are driven by the unequal heating between the equator and the poles. The tropics intercept a much larger fraction of the incoming solar energy than do the polar zones, thus giving rise to the motions that regulate the climate.

The point to be made here is that marginal, seemingly small changes in zonal or hemispheric means could, in turn, cause large changes in local regions that are near boundaries of different circulation regimes. But even if one of these shifts did occur, it would not necessarily mean that the "end of the world" has come. If the globe warmed up a degree or two and if the U.S. corn belt then moved from the Iowa area northward by a few hundred kilometers, the result might be but a small perturbation from a global evolutionary point of view to world food supplies and the earth's carrying capacity. However, in the present world situation in which people are locked into national boundaries, and there is little global food reserve, such marginal shifts could be serious (see the discussion in Schneider and Mesirow, 1976). Since crops are usually planted based on the pre-existing climatic conditions and their expected continuance, slow and gradual changes can be anticipated before crops are planted, thus perhaps avoiding a crisis. One of the main points to make here is that if changes should come quickly, a catastrophe might well result.

What causes the climate to change? Obviously, the output of the sun is very much implicated. Figure 1.4 (Thompson, 1973) is a plot of the double sunspot cycle. Since there are not negative sunspots, the part below the *X* axis is just the second half of the double sunspot cycle when the magnetic polarity of the spots has reversed. The figure further shows that there have been droughts in the U.S. high plains that correspond to alternate minima in the double sunspot cycle. A question arises as to whether a new drought will be beginning in the late 1970's, since the sun has recently passed through another minimum. Problems, however, arise as to why there may be a good correlation here. One could ask: Why do something like droughts in the U.S. plains correlate with sunspots and not some other atmospheric variable represented by a long-term continuous record?

These droughts occur, apparently, in different parts of the plains, and they move around. Nor is their occurrence precisely timed with alternate sunspot minima. But, why do they occur in the plains? Others have looked for periodicities to match with the sunspot cycles, of which there are thousands of possibilities. The problem is this: without a physical connection one can get oneself in statistical trouble. Figure 1.5 (Stetson, 1937) shows an example of the sort of work that has been done in this area. Here, the sunspot number is correlated with the Dow Jones stock market average, and the quality of wine vintage, or number of automobiles. In Figure 1.6 (Stetson, 1937) there is an even more fascinating "correlation"— sunspot number and rabbit population. This type of correlation attempt may be disturbing to us as scientists; but perhaps vegetation is affected by sunspots. If one has a physical theory, then one has some confidence in such statistical correlations—that is, one could take a time series of the variability of the sunspot cycle and look around for geophysical phenomena like wine harvests or

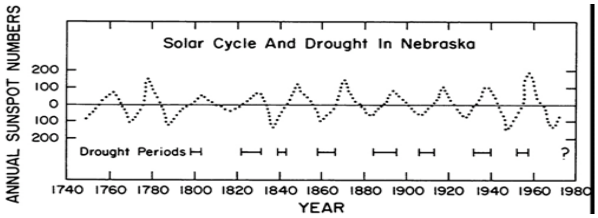

FIGURE 1.4 A plot of the double sunspot cycle versus drought in Nebraska. The graph suggests that droughts in the U.S. Great Plains tend to occur in a 22-year cycle centered near the minima of that cycle. If this relationship holds, then the next such drought is "due" in the last half of the 1970's (after Thompson, 1973).

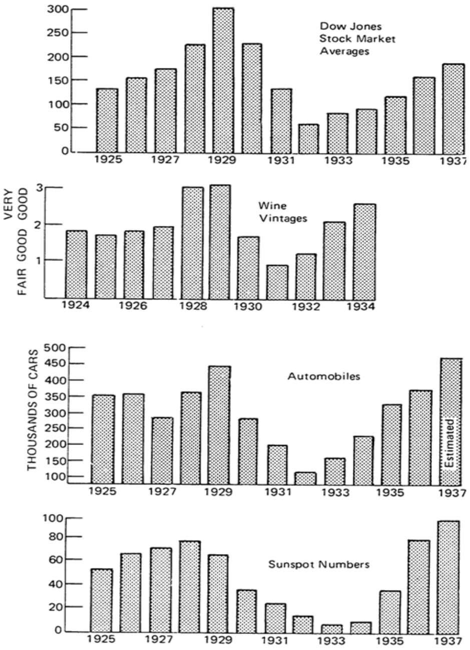

FIGURE 1.5 Plots of the Dow Jones stock market averages, wine vintages, and automobiles compared with the number of sunspots (after Stetson, 1937).

droughts, and then one might find some fit. But if one looked at a hundred of these possibilities and found one with 99 percent confidence, then one should question this kind of correlation on both statistical and physical grounds. On the other hand, there may be something physical there, nonetheless. But one must be extremely cautious.

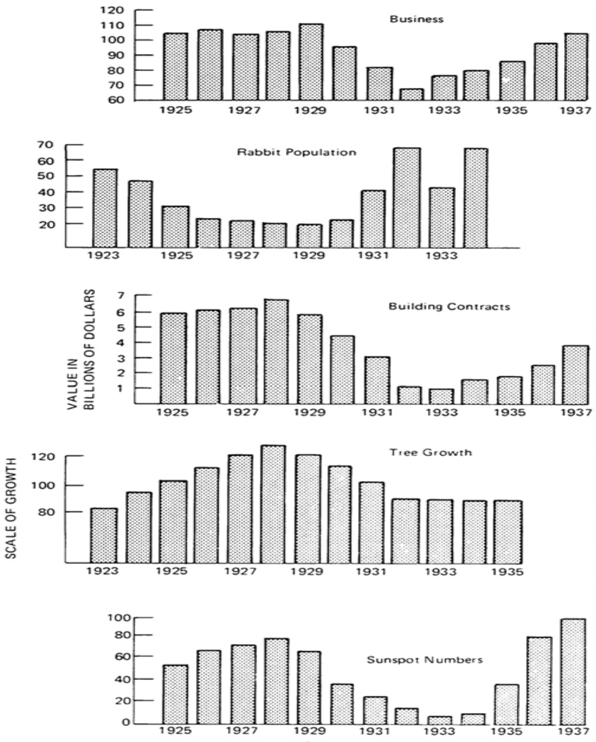

FIGURE 1.6 Plots of business, rabbit population, building contracts, and tree growth compared with the number of sunspots (after Stetson, 1937).

The fact is, of course, that sunspots are a visible manifestation of change on the element that provides us with our primary energy source. Could there also be a change in the “solar constant” with sunspots? Nobody has measured the solar constant to better than 1–2 percent. Yet present models indicate that a change of this magnitude would be sufficient to cause the kind of climatic changes seen in Figure 1.2. Eddy (1976), in his recent analysis of historical records, has shown that the sun may have lost its spots from about 1640 to 1700, which corresponds with the fairly consistent and strong temperature drop on most of the paleoclimatological records for this time. Whether or not this is indicative of change in the solar constant is still an open question (see Schneider and Mass, 1975). Again, why are the droughts seemingly localized near Nebraska, and why is the cycle not reflected in many other global records?

Some have invoked physical mechanisms other than solar constant variation with sunspots (e.g., Dickinson, 1975), namely, changes in the magnetic field of the earth, which modulate galactic cosmic rays, which create particles that form in the stratosphere, which, in turn, might make cirrus clouds, which can perturb radiation fluxes in the climatic system with enough energy to explain some terrestrial climate fluctuations. The real problem is that in the absence of either adequate measurement or adequate theory, one is basically left with the statistical correlations; and in the absence of theory, a fight is quite likely. At least at present there are some people seriously looking at the theoretical aspects of a solar–climate relationship.

Another possible cause of climatic change with supporting evidence is volcanic eruptions. Figure 1.7 (Ellis and Pueschel, 1971) shows the apparent transmittance of solar direct beam radiation at Mauna Loa in Hawaii at the 3000-m height observatory. In 1963, there was about a 2 percent drop in the direct solar radiation reaching the observatory, although 75 percent of this attenuated direct beam would still reach the surface because of scattering in the forward direction. This decrease occurred immediately following the Agung volcanic eruption. Note that roughly a half percent decrease in total solar energy reaching that station occurred and lasted for several years following that eruption. If model calculations are right, a decrease in solar radiation of that magnitude might drop the earth's global temperature on the order of several tenths of a degree. Volcanism is thus another potential mechanism of climate change.

On short time scales, and maybe even longer ones, there is always the possibility of internally caused climatic changes. The atmosphere could be viewed as a very fast oscillating device connected to the oceans by some spring, with the oceans being an even larger mass connected by a bigger spring to another mass, which are the glaciers. This whole system is an oscillatory one. By analogy, there is difficulty in determining whether some of the observed climatic changes are due just to the internal vibrations of this system, i.e., the redistribution of energy among the main reservoirs—the atmosphere, the oceans, and the glaciers—or are, in fact, due to external pushes by variations on the sun or by volcanoes. A problem lies in separating out the external factors—the volcanoes, the sun, or even carbon dioxide from human activities—from the internal redistributions. Based on essentially intuition, one might speculate that the shorter-time-scale fluctuations are internal, but the long-term changes are externally caused. The problem is that no quantitative theory of climate exists to end the intuitive speculations.

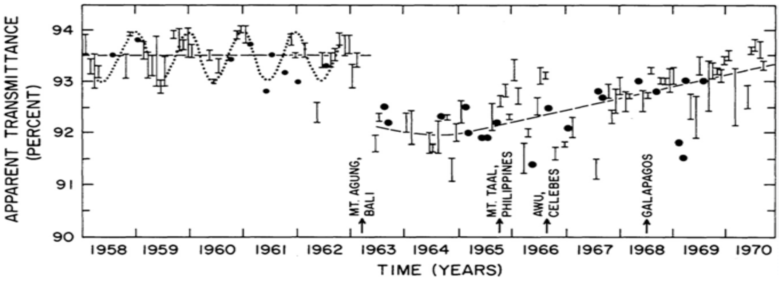

FIGURE 1.7 Plot of apparent atmospheric transmittance at Mauna Loa Observatory. Note the years of major volcanic eruptions (after Ellis and Pueschel, 1971).

CLIMATIC MODELS AS ESTIMATORS OF CLIMATIC CHANGE

There is one other important “externality” in the system, and that is people. Technically, this is not the traditional economic usage of the term “externality” (i.e., external economies or diseconomies). Since people are part of the biota, which are in our definition part of the climatic system, people are not truly an externality to the climatic system. However, in an important sense the social cost of many peoples' activities (e.g., those that release carbon dioxide to the atmosphere) does represent a situation where the producers (or users), who benefit from the activity that generates, say, this carbon dioxide, do not pay for the costs at the time of energy usage. Instead, the costs will be “externalized” to future generations. Thus, the analogy to the economic meaning of externality is valid.

Figure 1.8 (a) is a graph from a projection made in 1971 (Machta, 1971) of the carbon dioxide concentration in the atmosphere. Burning of fossil fuels puts carbon dioxide into the atmosphere, of which roughly a half to three fourths stays in the air, with the remaining fraction taken up by the oceans and biosphere. It also appears reasonably certain that an increase in carbon dioxide would affect the radiation balance of the earth in such a way as to warm the earth's surface. But quantitatively, how much of a heating might occur is another unanswered question. One has to go to a model to make such estimates because there are no available historical data to perform an actuarial study. There is no analogy in geological history (recent at least) from which one can obtain a scaling factor for the climatic response to anthropogenic physical laboratory experiments (which in fact do not really exist in this case).

It is probably true that these theoretical models of the CO_2 radiation effect have some observational justification. After all, one can predict the surface temperatures and the vertical temperature profiles of the CO_2 atmospheres of Mars and Venus, albeit not perfectly, but they still agree somewhat with the observations of those planets. This gives some indication that the models are not two orders of magnitude off. However, the issue as to the quantitative accuracy of the models remains. Models show that the increase in temperature from about 1900 to 1975 should have been on the order of a few tenths of a degree globally because of the increased carbon dioxide (see Figure 1.8). Therefore, one could argue that the carbon dioxide theory has been proved wrong by the fact that the northern hemisphere, at least after 1945, has cooled even though CO_2 increased exponentially. How

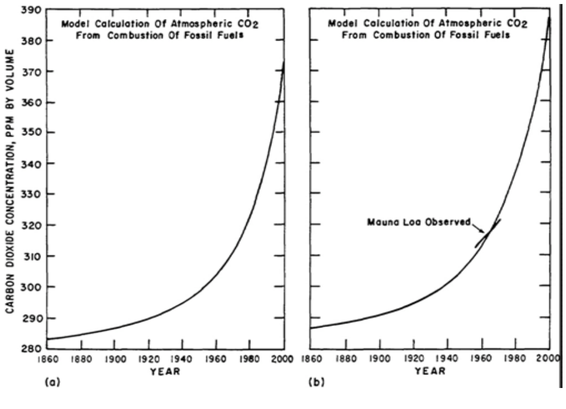

FIGURE 1.8 Projections of atmospheric carbon dioxide concentration from fossil fuels calculated by models of the carbon dioxide cycle. Projection (a) shows an early estimate of 375 parts per million (ppm) CO_2 concentration by the year 2000, whereas an updated model (b) predicts a CO_2 concentration of near 390 ppm. Projection (a) is from Machta (1971), and projection (b) is from Machta and Telegadas (1974).

ever, since the fluctuations in global temperature that have occurred naturally before humans could have had any real impact have been on the order of 1/2°C, or perhaps even larger, the cooling does not eliminate the CO_2 warming argument. Therefore, when a model predicts a change on the order of a few tenths of a degree, it is impossible to distinguish this carbon dioxide temperature "signal" from the natural climatic "noise." Thus it cannot be said categorically that the theory is incorrect. However, carbon dioxide in the atmosphere is increasing exponentially. According to most projections, the next 10 percent increase would occur in about two decades with the subsequent 10 percent increase in about one decade. As Broecker (1975) indicated, one may then certainly expect the CO_2 effect to exceed the climatic noise level; that is, if the modeling predictions are correct, the signal will become dramatically detectable very quickly (he projects sometime after 1980).

A test for the verification of these models is for them to show a high degree of faithful reproduction of atmospheric variability. Yet, on the other hand, a test of these models for *sensitivity* (to CO_2 increase, e.g.) is very difficult to devise. One is left with the terrible dilemma that in order to verify this kind of climate change (i.e., a detectable, significant climatic change from CO_2 possibly as early as a generation away) one uses a tool that itself is not entirely verifiable. Perhaps the only way, in a sense, to eliminate this problem is to have the atmosphere itself "perform the experiment" and verify the models. Aside from the environmental and social risks of such a happening, this implies that a model is substantially complete or at least contains the predominant physics, chemistry, and other mechanisms. This example of CO_2 uncertainties is typical of a large class of climatic problems at present.

FOOD-CLIMATE CONSIDERATIONS

Consider at this point some of the food–climate issues. Figure 1.9 shows a record of corn yield in Missouri (Decker, 1974). The solid line is an average trend over the last 70 years; the dots are the individual yields, that is, the number of bushels per acre for the state's area, and the squares represent the yields in the drought years. One notices that a tremendous increase in yield occurred after about 1940, and this is particularly noticeable in the 1950's, 1960's, and early 1970's. There is no question that this increase was caused by technology, that is, crop strains had been developed that could have higher yields and that were especially responsive to fertilizer applications or the use of pesticides. It is also seen on this figure that the relative percentage of yield variability (especially during the dust bowl period and the last drought in the 1950's) was very high relative to the variability in crop yield that has occurred recently (1956–1973).

Technology has been given credit by some for both of the above improvements. But McQuigg *et al.* (1973) showed that the period from 1956 through about 1973 was also an extremely unusual one weatherwise. As Figure 1.10 (Gilman, 1974) shows, that period differs from many other periods in climatic history. For example, the summer rainfall and summer temperature in the five major wheat states in the United States during the 1930's "dust bowl era" were below normal and above normal, respectively, and this combination is bad for crops. One should note that there still is much noise in the system including another drought in the 1950's (coincidentally 20-some years away from the previous one). But there is an unobtrusive looking 16-year period from 1957 to 1973, which may be called the "high-yield era" and shows (with one exception) all years with normal or above-normal rainfall and normal or below-normal temperature, which is in fact *abnormally good* for crops. However, there is no physical reason to expect that this abnormal trend will continue. When one plans for food at least, one cannot look only at a period of 15 years; one needs to look at periods longer than that in consideration of the future (see the discussion in Chapter 4 of Schneider and Mesirow, 1976).

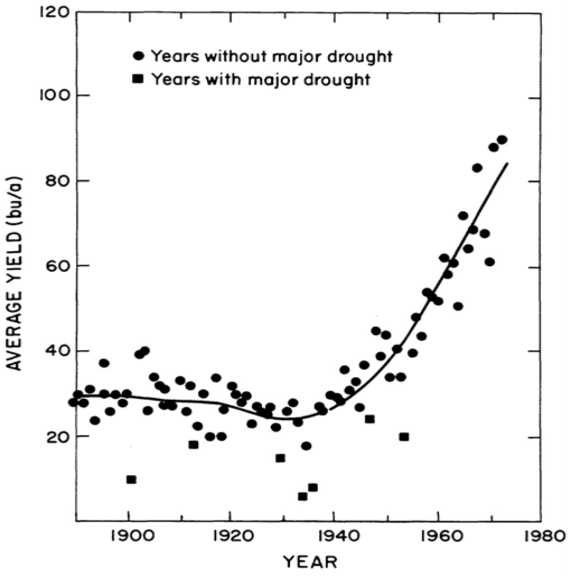

FIGURE 1.9 Solid line is the trend in corn yield per acre in Missouri (after Decker, 1974). The circles represent individual yearly yields for years without major drought, and the squares are for years with drought. Note that since 1956, not only have yields increased significantly but variability in yields from one year to the next has been reduced.

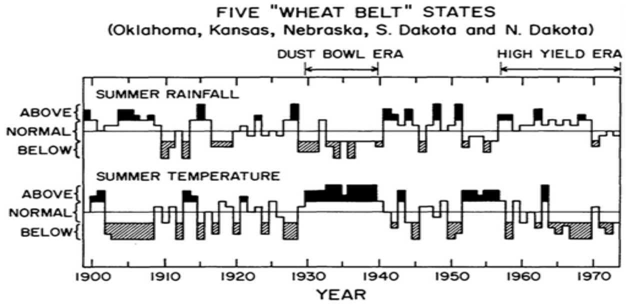

FIGURE 1.10 Seventy-five-year record of summer average temperature and rainfall in the five major wheat-producing states of the United States, compiled by Donald Gilman of the National Weather Service and showing the 10-year drought period (i.e., high temperatures and low rainfall) of the dust bowl era and the 15-year recent high-yield era (i.e., above average rainfall and below-average temperature).

RELATION TO WATER-SUPPLY ISSUES

Two conclusions are now applicable to the water-supply issue. The first suggests that one should accumulate data over a fairly long period in order to obtain some actuarial frequencies of the kinds of fluctuations that one might expect. Perhaps this would be centuries for reliable statistics, but it is at least 20 years. The second conclusion is that even though a time series may look stationary if viewed from "far enough back," a closer view might reveal that over a much shorter and more recent climatic sample period changes could be occurring because of human effects. Furthermore, these changes could be rather substantial in the next 20 to 50 years and may well change not only climatic means but also the frequencies of the shorter-term fluctuations. In essence, the real message here is that if we must contend with climatic uncertainty due to the natural fluctuations, that uncertainty will probably be greater in the future because there is a good possibility that the climatic system's boundary conditions are also changing—perhaps from human activities.

There should now be added one other point. In the only perfect forecast ever made—by Joseph in the Book of Genesis—he warned of seven years of feast and seven years of famine and, of course, proposed the solution of prudence in the face of environmental variability— namely, a food reserve. Now, whether what Schneider and Mesirow (1976) have called "The Genesis Strategy" for food reserves also applies by analogy for water-supply planning as part of the solution to an expectation of climatic uncertainty or whether planning should rather be to make society less vulnerable to the kinds of fluctuations that have occurred in the past few centuries are issues that need to be debated further. The one thing that is very clear is that climatic variability has been the rule in the past, but now there are additional unknowns produced by people, so it certainly would be prudent to expect considerable variability in future climate.

FINDINGS AND RECOMMENDATIONS

1. The climate varies on all time scales, and the meaning of climatic change depends on the defining period for the climatic average.
2. The climate of the past century or two is not necessarily typical of the climate over the past few thousand years, particularly on a regional scale.
3. Theory is yet unable to predict the future climate, so an actuarial analysis of recent past records, while not guaranteed valid, is probably the best quantitative way to estimate the range of future climatic variability. *However,* there is considerable numerical modeling evidence to the effect that human activities, i.e., production of CO_2, could *detectibly* change the "equilibrium" climate by as early as A.D. 2000 and that such a disruption could also change the patterns of climatic variability as well as climatic means.
4. World food supplies are very dependent on climatic stability, and world food supplies and needs are currently in a precarious balance that depends on large food transfers and stable supplies of fertilizer, water, and seeds. Population growth in the face of unstable or fluctuating food supplies, i.e., the classical Malthusian problem, may change agricultural demand for water in the future. At least, the implications of this tight margin for reserves of both food and water need to be examined.
5. The implications of these long-term growth (demand) and needs (supply) projections should be examined in the context of hedging, and the choice must be clarified as a value judgment fundamentally contrasting short-range economic benefits versus long-range catastrophic risks.

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2

Interpretation of Past Climatic Variability from Paleoenvironmental Indicators

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INTRODUCTION

The primary objective of this panel is to evaluate the national water supply in light of climatic variability. The following questions then arise: How crucial is knowledge of climatic variability to the design and operation of a water supply system, its reservoirs, and its distribution system? Should we incorporate newly gained knowledge of climatic change into the design and operation of such systems? If so, how much does climate vary? Can the variability be established on the basis of historical records? What is the probability of climatic change in the next 25 to 50 years?

We must first define what we mean by weather and climate. According to the Department of Transportation Select Panel assessing the variability of the climate (Mitchell *et al.,* 1975), the term “weather” refers to the total array of atmospheric conditions varying with time and location on the earth's surface. “Climate” connotes “average weather” but can be viewed from two perspectives:

1. A purely statistical approach in which climate is the sum of the weather as experienced at a point or over a designated area of the earth for a given period of time.
2. A physical concept that recognizes climate as a basic physical entity and weather as the momentary, transient behavior of the atmosphere attempting to satisfy the requirements dictated by the climate for horizontal and vertical transfer of mass, momentum, and energy.

There seems to be disagreement even among experts as to the need for understanding climatic variability in relation to water supply. There are those who believe that, since most projects in water resources have an economic life of from 40 to 100 years, and since there appears to have been little or no obvious climatic change over the past 200 years, the chance for natural climatic change in the next 200 years is minimal, and, therefore, the question is academic. For example, Chin and Yevjevich (1974) purported to show that climatic variation could be reduced to a deterministic component based on the Milankovich theory of astronomical cycles and a simple

Markovian stochastic component. From this position they went on to state that "since most systems have been built with the economic project life in the range 40 to 100 years, the chances are minimal that the expected natural water supply would be significantly different during these life spans than in the past 200 years." Furthermore, "this question is, however, not crucial for the next several generations of contemporary earth population, but rather is more of an academic interest like many other human concerns with the long-term future."

On the other hand, there are those who argue that climatic variability is a part of life on the planet earth and that it is to our advantage to recognize it, understand it, and take it into consideration in our planning processes. For example, Wallis and O'Connell (1973) studied the power of various statistical tests to distinguish small samples taken from Markovian and more persistent generating mechanisms. They concluded that statistical tests based on records of normal hydrologic length would usually lead one to believe that a Markov generating mechanism adequately represents hydrologic reality; however, because the tests have no power, this belief, while comforting, is likely to be erroneous. In a companion study, O'Connell and Wallis (1973) showed that Markov and more persistent generating mechanisms could lead to very different estimates of reservoir firm yield for 50-year design lives even when the generating mechanisms used yielded samples with identical expected values for the mean, variance, and lag-one correlation. They concluded that it was essential that hydrologists and water-resource planners understand the nature of climatic variability and persistence.

A similar position was taken by Mitchell *et al.* (1975), who stated:

The climate of the earth is now known beyond any doubt to have been in a more or less continual state of flux. Changeability is an evident characteristic of climate on all reasonable time scales of variation, from that of aeons down to those of millennia and centuries. The lesson of history seems to be that climatic variability is to be recognized and dealt with as a fundamental quantity of climate, and that it should be potentially perilous for man to assume that the climate of future decades and centuries will be free of similar variability.

The issue seems to revolve around the question, "How variable has climate been in the past?" Presumably, if atmospheric behavior is random in time, the definition of climatic variability would be a straightforward exercise in classical statistical sampling theory. One could estimate climatic variability as precisely as desired merely by choosing a long enough averaging interval. The problem here is that, as we go back in time, our data base diminishes and knowledge of atmospheric variability becomes less detailed and reliable. However, we do know enough about past climates to establish that long-term atmospheric behavior does not proceed randomly in time. Variations of climate from one geological epoch to another, and from one millennium to another, are clearly too large in amplitude to be explained as random deviations from modern averages.

How, then, do we study long-term variability? Unfortunately, climatic measurements do not extend back much

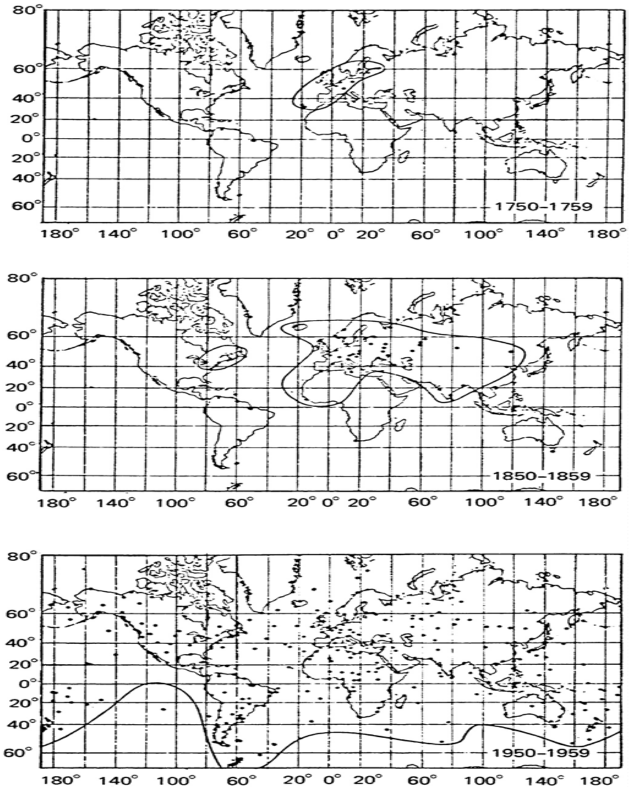

FIGURE 2.1 Growth of the network of surface pressure observations and of the area that can be covered by reliable 10-year average isobars (Lamb, 1969).

beyond the 1900's on any kind of an adequate spatial coverage. Lamb (1969) shows this well in three maps illustrating the growth of the network of surface barometric pressure observations and of the area covered by reliable 10-year-average isobars (Figure 2.1). Obviously, any intensive global or even hemispherical study of climatic variability from *instrumental records* is limited to the relatively short period 1900 to present. Even on a more local basis, the longest continuous time series of instrumental observations covers less than three centuries.

Therefore, for longer time scales, climatic variations must be inferred from historical evidence and from the records of various natural phenomena linked in some way to climate. Such *paleoclimatic indicators* (Table 2.1) differ greatly in the time spans over which they are applicable, in the degree of climatic detail they can provide, in the aspects of climate to which they respond, and in the fidelity of their response.

Reconstructions of the paleoclimatic record can lead one to believe that changes of climate, such as those associated with alternating glacial and interglacial stages of the Pleistocene, are smoothly varying functions of time, readily distinguishable from the much more rapid variability of year-to-year changes of atmospheric state. Hence, to give a stable estimate of present-day climate, the averaging interval would have to be long enough only to suppress year-to-year sampling variability but short in comparison with the duration of a glacial period. Unfortunately, the apparent “smoothness” of atmospheric change in the geological past is only an illusion, attributable to the inadequate resolving power of paleoclimatic indicators. Most such indicators act to some degree as low-pass filters of the actual climatic chronology. Our more recent experience, based on relatively higher-pass filters such as tree rings, varves, ice-cap stratigraphy, and pollen analysis applicable to postglacial time, suggests that the state of the atmosphere has varied on most, if not all, shorter scales of time, as well as over the longer geologic time scales.

TRANSFER-FUNCTION ANALYSIS

Since about 1960, advances in mathematical and statistical techniques and the availability of high-speed computers that enable researchers to handle large amounts of data have for the first time made it possible to quantify climatic parameters derived from secondary sources (Fritts *et al.*, 1971; Webb and Bryson, 1972). Furthermore, these quantified climatic parameters are provided in a form suitable for input into dynamic models of atmospheric circulation (CLIMAP Project Members, 1976). By providing quantitative data for past conditions, it is becoming possible to model the dynamics of past circulations and to test existing models of the present circulation with regard to their power of explanation (Gates, 1976). At the heart of these quantitative paleoclimatic records is the concept of transfer-function analysis.

Let the matrix X be a defined set of response variables that respond to climate measured over a specified realm of time and space. Let C be a measured set of physical indicators of climate, atmospheric or marine, measured over the same time–space realm and assumed to be causally related to X. Let D be another set of physical parameters of the system, independent of the response of X. (D would typically include nonclimatic effects.) Then if $D = 0$, the system consists of X, C, and a set of *climatic response functions* R_e such that

$$X = R_e(C). \quad (1)$$

If $D \neq 0$, the *total response function* R_t must be considered, and

$$X = R_t(CD). \quad (2)$$

The result is calibration of the climatic signal inherent in the secondary series X, with measured values of the climatic variable or variables of interest.

A fundamental problem of quantitative paleoclimatology is to find a set of *transfer functions* φ such that C can be estimated given X; i.e.,

$$C = \varphi(X). \quad (3)$$

Generally, φ is obtained by direct empirical methods and not by inversion of R_e (or R_t). The X and C used to derive the transfer function are the calibration data set. The X to which the transfer functions are applied is the climatic reconstruction data set.

In the use of any transfer function, the investigator must make several basic decisions. There are fundamental problems concerning the assumptions used in writing any transfer function. Principal among these is the use of “the present as a key to the past.” For example, if elements of the biota (in ocean-sediment samples) have evolved since the fossil deposit was formed, the calibration and reconstruction data sets are nonhomogeneous. Another problem is the no-analogue situation, for which fossil values of certain taxa exceed the modern values used to derive the transfer functions. Both problems exist in tree-ring analysis. It is assumed that a tree responds to climatic inputs in a similar fashion throughout its lifespan such that one can make a homogeneous transition between the calibration data set and the reconstruction data set via the transfer function. One can conceive of a no-analogue situation wherein climatic events that have occurred in the past are not present in the calibration data set.

As a direct test of any transfer function, the reconstructed data must withstand some sort of validation test to determine the accuracy of estimates of past climate. In general, five techniques are currently being used:

1. Direct check: In tree-ring work, meteorological records are used to validate estimates of the reconstructed climate. This usually requires “holding back” some portion of the measured record from the calibration process for use in checking reconstructed values.

TABLE 2.1 Characteristics of Paleoclimatic Data Sources (after Kutzbach, 1975)

Data Source	Variable Measured	Continuity of Evidence	Potential Geographical Coverage	Period Open to Study (yr)	Minimum Sampling Interval (yr)	Usual Dating Accuracy (yr)	Climatic Inference
Ocean sediments (cores, < 2 cm/1000 yr)	Isotopic composition of planktonic fossils; benthic fossils; mineralogic composition	Continuous	Global ocean	1,000,000 +	1000 +	±5%	Surface temperature, global ice volume; bottom temperature and bottom-water flux; bottom-water chemistry
Ancient soils	Soil type	Episodic	Lower and midlatitudes	1,000,000	200	±5%	Temperature, precipitation, drainage
Marine shorelines	Coastal features, reef growth	Episodic	Stable coasts, oceanic islands	400,000	—	±5%	Sea level, ice volume
Ocean sediments (common deep-sea cores, 2–5 cm/1000 yr)	Ash and sand accumulation	Continuous	Global ocean (outside red clay areas)	200,000	500 +	±5%	Wind direction
Ocean sediments (common deep-sea cores, 2–5 cm/1000 yr)	Fossil plankton composition	Continuous	Global ocean (outside red clay areas)	200,000	500 +	±5%	Sea-surface temperature, surface salinity, sea-ice extent
Ocean sediments (common deep-sea cores, 2–5 cm/1000 yr)	Isotopic composition of planktonic fossils; benthic fossils; mineralogic composition	Continuous	Global ocean (above $CaCO_3$ compensation level)	200,000	500 +	±5%	Surface temperature, global ice volume; bottom temperature and bottom-water flux; bottom-water chemistry
Layered ice cores	Oxygen-isotope concentration (long cores)	Continuous	Antarctica; Greenland	100,000 +	Variable	Variable	Temperature
Closed-basin lakes	Lake level	Episodic	Lower and midlatitudes	50,000	1–100 (variable)	±5%	Evaporation, runoff, precipitation, temperature
Mountain glaciers	Terminal positions	Episodic	45° S to 70° N	50,000	—	±5%	Extent of mountain glaciers
Ice sheets	Terminal positions	Episodic	Midlatitudes to high latitudes	25,000 (common) 1,000,000 (rare)	—	Variable	Area of ice sheets
Bog or lake sediments	Pollen-type concentration, mineralogic composition (normal core)	Continuous	50° S to 70° N	10,000+ (common) 200,000 (rare)	200	±5%	Temperature, precipitation, soil moisture
Ocean sediments (rare cores, > 10 cm/1000 yr)	Isotopic composition of planktonic fossils; benthic fossils; mineralogic composition	Continuous	Along continental margins	10,000+	20	±5%	Surface temperature, global ice volume; bottom temperature and bottom-water flux; bottom-water chemistry
Layered ice cores	Oxygen-isotope concentration, thickness (short cores)	Continuous	Antarctica; Greenland	10,000 +	1–10	±1–100	Temperature, accumulation
Layered lake sediments	Pollen-type concentration (annually layered core)	Continuous	Midlatitude continents	10,000 +	1–10	±1–10	Temperature, precipitation, soil moisture
Tree rings	Ring width anomaly, density, isotopic composition	Continuous	Midlatitudes and high-latitudes continents	1000 (common) 8000 (rare)	1	1	Temperature, runoff, precipitation, soil moisture
Written records	Phenology, weather logs, sailing logs, etc.	Episodic	Global	1000 +	1	1	Varied
Archeological records	Varied	Episodic	Global	10,000 +	—	Varied	Varied

2. Comparison of two or more independently derived biologically based transfer functions: In ocean-sediment analysis this could mean comparing results obtained by using radiolaria to those obtained by using foraminifera. In continental regions, the results obtained by pollen analysis can be compared with those obtained by tree-ring analysis, or results based on tree-ring data from one site can be compared with those from another location.
3. Comparison of isotopic and biologically based estimates: Results obtained by isotopic analysis of fossil remains taken from ocean-sediment cores should correspond to those derived from species associations.
4. Concordant estimate: Independently derived transfer function applied to the same paleoclimatic indicator should produce similar results. Discord can result from the application of two different transfer functions based on one paleoenvironmental group or perhaps from use of one transfer function on more than one group of variables.
5. Synoptic consistency: On an intuitive basis, the spatial pattern and absolute range of synoptic maps of reconstructed climate must conform within reasonable variations. Using the high-speed computer and numerical simulation techniques, intuitive evaluations can be made more rigorous and inclusive. In the end, reconstructed climatic data from all sources listed in Table 2.1 must fit together temporally.

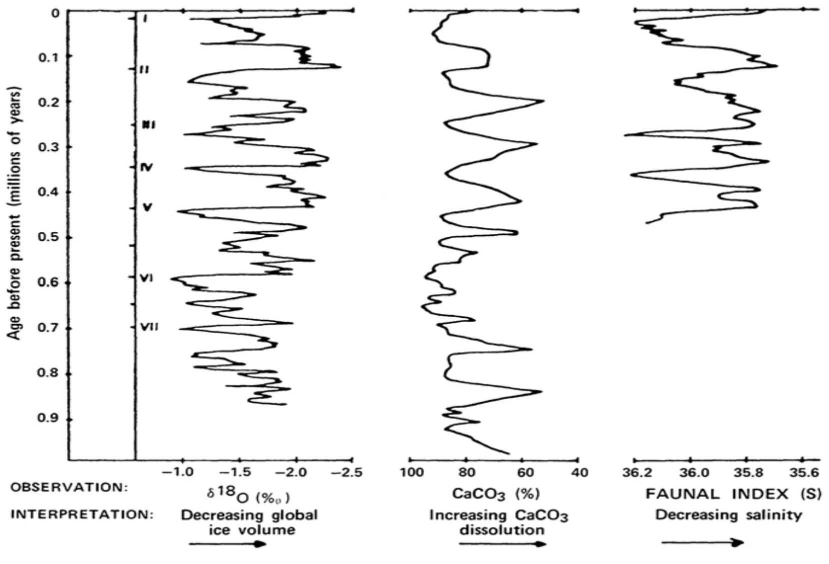

FIGURE 2.2 Comparison of paleoenvironmental indicators of climatic records for the past 1,000,000 years. Roman numerals indicate inferred climatic periods (modified from Figure A. 14, U.S. Committee for the Global Atmospheric Research Program, 1975).

Another type of problem inherent in the use of transfer functions to derive paleoclimatic information is associated with the mathematical manipulation of the data. Obviously, the researcher wants to choose the transferfunction technique that is most robust against various types of distortion, most precise in terms of error, and most accurate in terms of reconstructed climatic values. Referring to Eq. (3), at least three such problems can be singled out for appraisal.

The first problem is the selection and proper application of appropriate statistical techniques. Generally, some sort of multivariate technique is used. When this is the case, eigenvectors are usually used as a mode of joint behavior classification. A question then arises as to what criteria should be applied for inclusion and whether to use some sort of rotation. Most models currently being used are linear. Is it valid to assume linearity, and, if not, how does the use of a linear model affect the final results? Is it the best policy to utilize transformations?

The second problem includes specifying the kinds of variables to be included in X and the space and time to be covered. Under what circumstances does φ not exist? How does one define the distribution of samples in time and space to be used in the calibration data set?

The third problem is the selection of variables and valid estimates of them for inclusion in matrix C. These data must represent a homogeneous reconstruction. For example, what climatic (or environmental) variables are most likely to influence the response and to what degree? Is the relationship linear, and, if not, is it reasonable to assume that the response can be approximated by a linear relationship? Is it wise to use secondary forms of variables such as barometric pressure when it is known that the response is tied directly to such variables as precipitation and temperature? Many biological and sedimentary monitoring systems show significant lag in their responses to climatic variation. It becomes essential to assess this effect and to include it in the transfer-function model.

RESULTS OF STUDIES

Although the recent attempts to quantify paleoclimate as derived from secondary sources are plagued with problems, the degree of coherence in spatial and temporal variation that is achieved between reconstructions derived from different sources by different investigators has been most encouraging.

Mitchell *et al.* (1975) have collected and assembled climatic interpretations based on secondary sources. These results have been used extensively in the rest of this section.

LONG-TERM PALEOCLIMATIC INFERENCES (GLOBAL AND HEMISPHERIC SCALE)

Major Ice Ages in the Past Billion Years

Geological evidence leaves little doubt that, during the past billion years or so, the prevalent condition of macro-scale climate was one of relative warmth—as much as 10°C warmer than now—and almost total absence of polar ice. This warm condition was, however, punctuated by at least three major ice ages, each around 10 million years long and separated by a few hundreds of millions of years. Beginning roughly 50 million years ago, something appears to have brought about a gradual cooling. This cooling trend culminated, about 2 million years ago, in the arrival of a new major ice age (the Quaternary), characterized by a long sequence of perhaps as many as 20 major glacial–interglacial oscillations, which presumably continue to grip the world today.

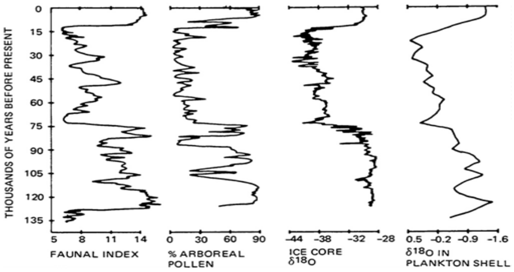

FIGURE 2.3 Comparison of paleoenvironmental indicators of climatic records for the past 135,000 years (modified from Figure A.13, U.S. Committee for the Global Atmospheric Research Program, 1975).

Glacial and Interglacial Stages of the Quaternary

Detailed evidence of conditions within the Quaternary shows that periods of glacial extension (glacials) and retraction (interglacials) have alternated in a fairly regular sequence (Kukla, 1961; Broecker and van Donk, 1970).

Figure 2.2 shows climatic records for the past million years as deduced from the geological and biological record. The first section of the figure shows the oxygen-isotope curve for Pacific deep-sea core V28-238, interpreted as reflecting global ice volume (Shackleton and Opdyke, 1973). The relatively rapid and high-amplitude fluctuations are taken to indicate sudden deglaciations and are designated as the terminations I to VII. The second section shows the calcium carbonate percentage in equatorial Pacific core RC11-209 (Hays *et al.,* 1969). Low values are taken to indicate periods of rapid dissolution by bottom waters. The third section shows the faunal index, reflecting changing composition of Caribbean foraminiferal plankton, calibrated as an estimate of sea-surface salinity in parts per thousand (Imbrie *et al.,* 1973). Glacial periods are marked by the influx of plankton preferring higher-salinity waters (Prell, 1974). Note that each of the three records reflects a climatic fluctuation or “cycle” averaging about 100,000 years. This is particularly true during the past 450,000 years. Each cycle started with a short interglacial and ended with an equally short extreme glacial peak. These extremes represent only 20 to 30 percent of the total duration of a typical cycle (length about 100,000 years), and the glacial itself can usually be subdivided into relatively warm interstadials and cooler stadials.*

At the peak of the last glacial, 17,000 to 18,000 years ago, an ice sheet 2 km thick covered the northern and middle latitudes of North America as far south as New York, and another sheet in Europe reached as far south as Hamburg, Berlin, and Warsaw. Smaller ice caps and valley glaciers covered large areas of the Rockies, Alps, Andes, Hindukush, and many other mountain ranges. Because the volume of ice on the continents was some 50×10^6 km^3 greater than today (Flint, 1971), the oceans stood about 100 m below their present level (Bloom, 1971). Atmospheric and oceanic circulation, as reconstructed from available surface characteristics, greatly differed from present means (Lamb, 1971). The mean annual temperatures were lower by about 3°C at the equator and 10 to 12°C in the midlatitudes of the northern hemisphere. The departure in the global mean was about 2°C (CLIMAP Project Members, 1976).

During glacial maxima, vegetational and faunal zones in temperate regions were displaced to lower altitudes and latitudes as compared with their interglacial loca

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*Interstadials are regarded as moderately warm interglacial periods not as extremely warm as present-day conditions. Similarly, stadials are moderately cold.

tions. Highly continental climate, dry and with cold winters, characterized Europe and Central Asia. As a result, tundra and steppe replaced the pre-existing forests (Frenzel, 1967). Greater continentality and desiccation are similarly indicated for parts of Africa and South America (Fairbridge, 1972).

Figure 2.3 shows climatic records for the past 135,000 years: (a) A faunal index reflecting changes in foraminiferal plankton in a core west of Ireland. The index is an estimate of August sea-surface temperature in degrees Celsius (Sancetta *et al.,* 1973). (b) The percentage of tree pollen accumulated in a Macedonian lake (Van der Hammen *et al.,* 1971). High values indicate warmer and somewhat drier conditions, (c) Oxygen-isotope ratio expressed as ^{18}O in an ice core at Camp Century, Greenland. This is interpreted as indicating changing air temperatures over the ice cap (Dansgaard *et al.,* 1971). (d) Oxygen-isotope ratio in skeletons of planktonic foraminifera in a Caribbean core, interpreted as changes in global ice volume. High negative values reflect the melting of ice containing isotopically light oxygen (Emiliani, 1964).

The interglacial periods were characterized by climate much like that of the recent past, with similar plant and animal distributions. These were periods of retracted ice sheets, high sea levels, and relative warmth.

The amplitude of the climatic variations associated with the glacial cycles seems remarkably constant. It is likely that global mean values of atmospheric or oceanic variables differed little between successive interglacials (Emiliani, 1973).

Postglacial Climatic History

Although comprehensive evidence is scarce, the earth is apparently now in an interglacial period. It began between 10,000 and 14,000 years ago with general warming accompanied by the decay of the continental ice sheets. The climate of this period is characterized by several marked fluctuations, which appear to have occurred mostly simultaneously in the northern and southern hemispheres. This is especially true (Heusser, 1966) for the drastic variations between 12,000 and 10,000 years before the present (B.P). The limited data currently available suggest that the cool and relatively wet climate of the period was suddenly replaced by a worldwide mild, even warm, period. Even more dramatic was the later catastrophic readvance of the ice masses about 10,800 B.P., which killed entire forests in a period of probably less than a century (Lamb, 1966).

If we disregard some minor fluctuations during the recession of the large continental ice sheets, which disappeared completely about 6000 B.C. in Scandinavia and about 4000 B.C. in northern Canada, the climax of the postglacial warming was reached between 5000 and 4000 B.C. This was once more a worldwide phenomenon, where the annual temperatures were 2 to 3°C warmer than today. Even in Alaska, they were more than 1°C warmer. This period has been defined as the “postglacial optimum” or “hypsithermal.” Its mild climate, together with the relative dryness in large areas of North America and the Soviet Union, suggests a poleward displacement of the subtropical anticyclonic belt. The arctic sea ice had receded well north of its present position, but there exists no evidence for a complete disappearance of its central area north of about 80° latitude. At the same time (and after), the Sahara and the arid parts of the Near East were considerably more humid; this means that in now completely barren, arid areas there was a steppe vegetation produced by occasional severe rainstorms. Some evidence also exists for a northward extension of the tropical summer rain belt (Lamb, 1966). During this time, many smaller mountain glaciers completely disappeared, and the snow line was about 300 m higher than today. The sea level gradually rose to its present level but not above it (Shepard and Curray, 1967); after this date it was mainly controlled by the mass budgets of Antarctica and Greenland. A cool episode occurred between 4000 and 3000 B.C., signaled by the re-formation or expansion of mountain glaciers, followed by renewed warming (Figure 2.4). Cooling and glacial advance took place again between 1400 and 500 B.C. The subsequent warming trend ended before A.D. 600, at least in western North America, where glaciers again advanced, culminating about A.D. 900.

The climatic record becomes increasingly detailed and reliable beginning about 1000 years ago, mainly because of the availability of historical accounts in at least the North Atlantic sector. The mild conditions of the postglacial optimum were nearly reached once more during the early Middle Ages, culminating about A.D. 1200 when ice conditions around Iceland and Greenland were much less severe than today (Figure 2.5). Annual mean temperatures in southern Greenland must have been 2 to 4°C above present averages (Table 2.2). Oxygen-isotope ratios in the Greenland icecap (Figure 2.6) confirm the warmer climate there during this period. In England (Table 2.2

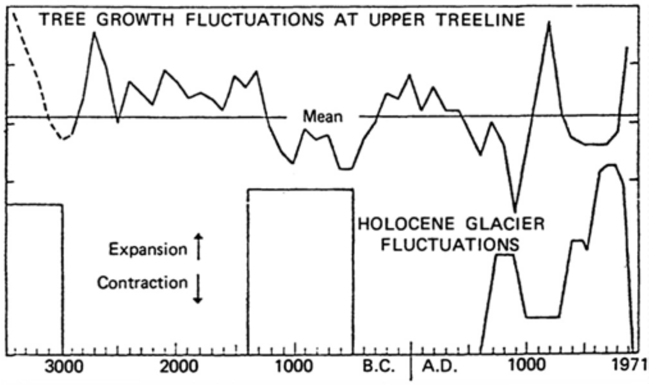

FIGURE 2.4 Periods of low tree growth and glacial advance indicating cool periods in late Holocene time. Tree-ring data are from California; glacial data are mainly from northern hemisphere (Denton and Karlén, 1973; LaMarche, 1974).

and Figure 2.7), mean annual temperatures were about 1°C above recent normals. In contrast to the situation of A.D. 500 to 900, when pronounced cooling of western North America is apparently not reflected in the European record (Denton and Karlén, 1973), variations of the climate of these parts of the northern hemisphere seem remarkably similar during the past 1000 years.

TABLE 2.2 Average Climatic Conditions over England and Wales (after Mitchell et al., 1975)[a]

		Mean Temperatures (°C)			Annual rainfall (mm)	Annual evaporation (mm)
Dates (approx.)	Epoch	Summer (July–Aug.)	Winter (Dec.–Feb.)	Annual		
A.D. 1901–1950	Recent	15.8	4.2	9.4	932	497
A.D. 1550–1700	Little Ice Age	15.3	3.2	8.8	867	467
A.D. 1150–1300	Little Optimum	16.3	4.2	10.2	960	517
900–450 B.C.	Subatlantic	15.1	4.7	9.3	960–979	482

[a] After Lamb (1966).

Northern hemisphere data suggest that the period after A.D. 1300 was one of widespread change to cooler conditions; this period has been termed the historic "Little Ice Age." Glaciers advanced in many parts of the world, but this brief episode cannot be compared with the great glacials lasting several tens of thousands of years. Worldwide glacial recession accompanied global temperature rises after 1895.

Kutzbach and Bryson (1975) present plots of frequency versus percentage of variation in different climatic records. One of these is reproduced as Figure 2.8. From this diagram it is apparent that, based on well-dated temperature records from Central England and Iceland and an isotope record from Greenland, the data in the intermediate zone (500 to 1000 years) show considerable persistence and the data at the higher frequencies (10 to 100 years) are nearly random. The authors point out the shortcomings of the study, including the lack of replications from other records and the gap between periods of 500 and 1000 years, where spectral estimates are less reliable in a statistical sense. They also stress the need for defining details of the climatic spectrum in the intermediate range of 500 to 1000 years. Climatic fluctuations at these time scales can have great impact on water resources, yet this is the least known portion of the spectrum.

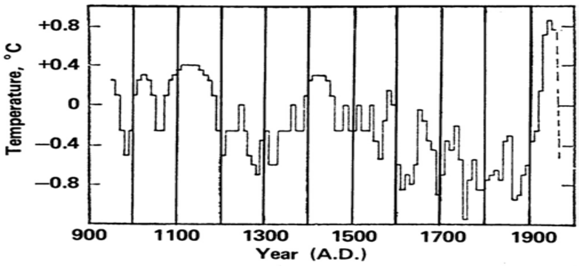

FIGURE 2.5 Departure of mean annual temperature in Iceland inferred from extent of sea ice during the past 1000 years. Departures from values for the period of meteorological record (Bargthorsson, 1962, as presented by Bryson, 1974).

REGIONAL EVALUATION OF PALEO-HYDROLOGIC PHENOMENA

It is now quite apparent that, although adequate data may be available for documentation of long-term climatic fluctuations on a global or hemispherical scale, the amount available for specific regions can be quite limited. However, recent studies have shown the type of regional hydrologic information that can be obtained from paleo-climatic indicators.

Within the framework of the national water demand criteria, we decided to focus on two distinct regions—the Southwest and the Northeast—for concentrated studies.

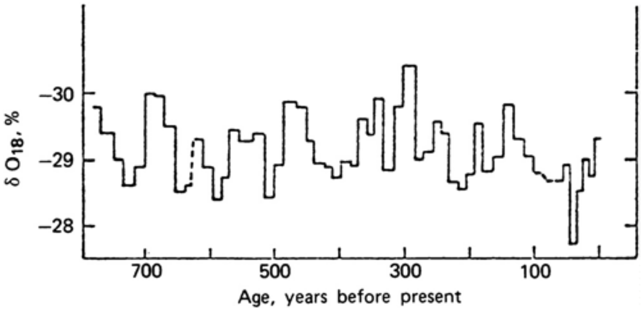

FIGURE 2.6 Oxygen-isotope ratios in ice from the Camp Century Core, Greenland. Low values (top of graph) indicate low temperatures. Vertical scale is relative departure of ^{18}O constant compared with a standard (Dansgaard *et al.,* 1971).

These areas are, respectively, one of the fastest growing areas of population and the area of present greatest population. We have attempted to accumulate long-term information concerning climate for these two regions.

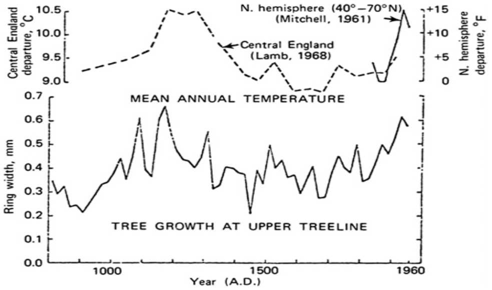

FIGURE 2.7 Estimated temperatures in Central England since A.D. 900 compared with tree-ring variations in California indicating general cooling in northern hemisphere between A.D. 1300 and 1900 (LaMarche, 1974).

Southwestern United States

Stockton (1975) and Stockton and Jacoby (1976) have attempted to show how long-term total annual runoff records can be reconstructed utilizing tree-ring data. Their study provides detailed reconstructions of total annual runoff for several subbasins within the Upper Colorado River Basin. In addition, it suggests that, within a larger basin, the tributary systems can show varying degrees of persistence. For example, Figure 2.9 shows the variance spectra computed for three tributary rivers within the Upper Colorado River Basin. The drainage areas of the three are not greatly different; however, the degree of persistence in the reconstructed records differs substantially. The Green River shows a greater tendency for low-frequency variation than either the Colorado above Cisco or the San Juan at Bluff. It appears that the tendency for long-term climatic persistence may be greater in the Green River Basin than for either the Colorado above Cisco or the San Juan above Bluff. This

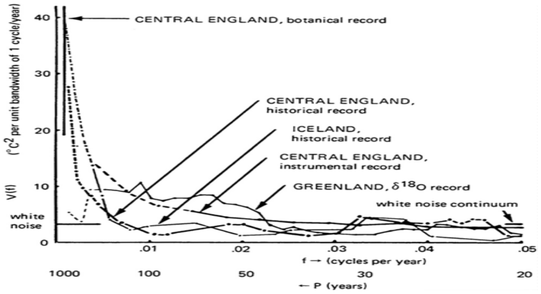

FIGURE 2.8 Composite variance spectrum of temperature on time scales of 10 to 10^3 years derived from instrumental, historical, botanical, and oxygen-isotope records (after Kutzbach and Bryson, 1975).

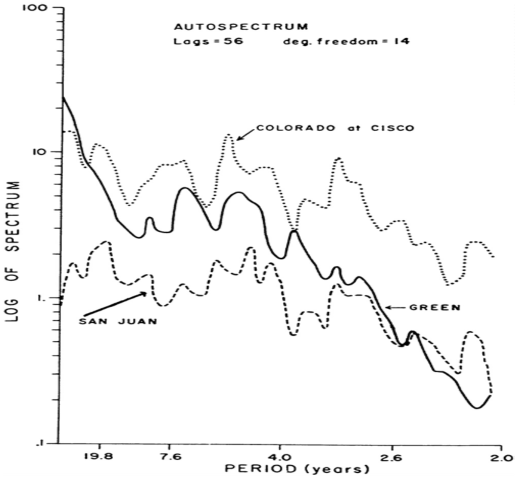

FIGURE 2.9 Comparison of the sample autospectral functions for the long-term reconstructed runoff records for the Green River at Green River, Utah; the Colorado River at Cisco, Utah (Colorado mainstem); and the San Juan River at Bluff, Utah (Stockton, 1975).

suggests the need for evaluation of paleoclimatic variation in rather limited areas.

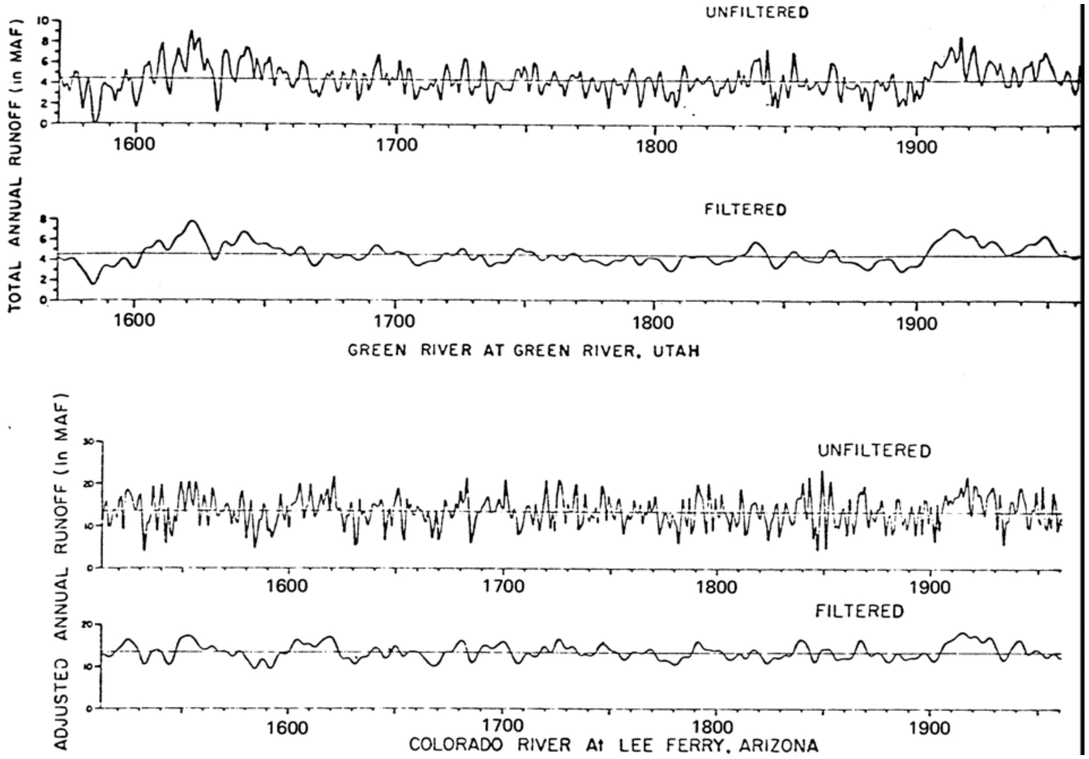

FIGURE 2.10 Reconstructed hydrographs for total annual runoff for the Green River at Green River, Utah, and the Colorado River at Lee Ferry, Arizona. In each case, the lower graph is the same data but with the high-frequency components (those with a frequency greater than 10 years) removed (Stockton, 1975).

The long-term hydrograph for the Upper Colorado River Basin as a whole does not exhibit the degree of long-term persistence that is found in the Green River reconstruction (Figure 2.10). However, analysis of the persistence does show that the series is significantly different from random and is best modeled by a mixed autoregressive-moving average scheme. In addition, the reconstructed hydrograph shows that the early part of the twentieth century was characterized by a period of anomalously high sustained flow, the longest in the entire 450-year reconstruction. The gauged record alone would not reveal this fact, so anyone depending solely on the gauged record would obtain inflated estimates of mean annual flow and variance. The reconstructed hydrograph is consistent with the secular variation shown in temperature trends as illustrated by LaMarche (1974) (see Figure 2.7). Also, the degree of persistence seems to be of the same magnitude as that suggested by Kutzbach and Bryson (1975) for records of similar length (Figure 2.8).

LaMarche (1973) studied tree-line changes in the White Mountains of east-central California and found that, between A.D. 1300 and 1600, abrupt climatic change resulted in lowering of the timberline some 70 m. He attributed this to an apparent climatic change to much colder summers or to fairly cold summers and drier springs, autumns, and winters. Judging from later work, this condition apparently lasted at least up to the early 1900's. This example serves to illustrate two points. First, that apparently climatic change can occur over a relatively short time period (hundreds of years) and, second, that there is additional evidence for the large flow anomalies as reconstructed in the hydrograph for the Upper Colorado River (Figure 2.10).

From the foregoing evidence, it appears that within the southwestern United States climatic change has occurred during the past 500 or so years, that it has occurred over a fairly short time span, and that it has been reflected in the annual runoff, at least for the Upper Colorado River Basin.

Northeastern United States

The only currently existing detailed regional analysis using historical data for the northeastern United States is by Landsberg *et al.* (1968). They used historical climatic records along the eastern seaboard, centered on Philadelphia, and a least-squares technique to reconstruct provisionally a 230-year record of temperature and precipitation (Figure 2.11). They noted a trend in the annual temperature data principally "caused by the lack of cold years since the turn of the 20th century." The trend is also confirmed by a variance spectrum analysis. No mention is made of the annual precipitation series, but Figure 2.11 illustrates the anomalous wet period extending from about 1830 to 1880.

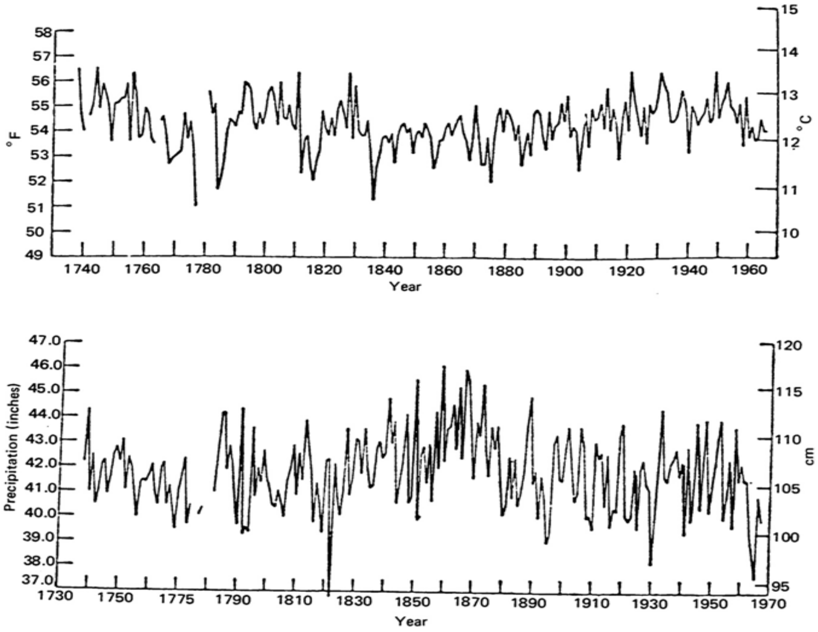

FIGURE 2.11 Annual temperatures and annual precipitation totals for the eastern seaboard of the United States for the period 1738–1967—a representative, reconstructed synthetic series centered on Philadelphia (after Landsberg *et al.*, 1968).

Although considerable paleoclimatic work has been done in the northeastern section of the United States, much of it is still qualitative. Many of the results are in the form of pollen data and tree-ring data.

Using pollen data, Webb and Bryson (1972) presented quantification of July mean temperature, summer precipitation, and precipitation minus potential evaporation for an area in north-central United States. This investigation was later expanded by Bryson (1974) to cover a larger area. These reconstructions cover the past 15,000 years and show an extreme temperature drop (as much as 8°C) at about 10,000 years B.P.

Blasing (1975) shows reconstruction of climatic types on a national scale and indicates that certain climatic anomaly patterns have been more prevalent during the previous two centuries than in this one. However, his conclusions are based on reconstructions of large-scale atmospheric circulation patterns, derived from tree-ring data in western North America.

CONCLUSIONS

The methods of quantitative paleoclimatology enable us to increase our knowledge of many details of climatic history. By increasing our knowledge of past climate, we gain a valuable perspective to our view of climate of the present and future.

There exist, at present, isolated time series that indeed suggest important climatic changes at all time scales. However, the job of transforming this information into spatial maps so that we can *study patterns* of change with adequate spatial detail is just beginning. Until these maps exist, we cannot accurately characterize periods as warm or cool, wet or dry except at specific locations. This will not occur without concentrated research efforts and considerable support in the future.

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II SOCIO-ECONOMIC CONSIDERATIONS

3

Methods for Estimating and Projecting Water Demands for Water-Resources Planning

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INTRODUCTION

Long-run solutions to problems associated with scarce natural resources and raw materials are of critical importance to the economies of industrialized nations. Water is undoubtedly one of the most critical of these scarce resources, although recently attention has been focused more upon various forms of energy. As both population and economic growth continue, there is an increasing need for the development of more effective planning models and strategies to meet the problems associated with expanding resource demands. In the market economies, except in times of extreme exigency, such as war, the allocation and distribution problems are solved by rising prices. The demand for certain resources is brought into balance with available supply at some new (higher) price level.

In economic theory the concept of "demand" for a particular commodity is the schedule of quantities of the commodity consumers are willing to purchase at various prices. While the concept can be precisely defined for any good or service, the task of giving it operational and empirical content with the same degree of exactness has traditionally been considerably more difficult. Economists have indicated on several occasions concern about the continuing use of the terms "requirement," "use," and "need" when referring to the withdrawal or intake of water as a natural resource.[1] These terms are called into question because they do not have an allocative connotation that is in keeping with the competitive market framework.

Given the general problems associated with statistical demand estimation and, in the case of water, present conditions of "block pricing" and substitute goods such as self-supplied, reclaimed, or recirculated water, the prospect for determining demand functions relating to water (particularly for water as a production input) for purposes of policy formulation may remain tenuous for some time to come.

In the sections that follow, the current state of the art of forecasting water demands or requirements is reviewed for the water-use categories of irrigation, minerals industries, manufacturing industries, thermoelectric power, commercial, and municipal. Water-resource systems planning and the role of water-use data in the development of water-use forecasts are discussed, and the possible impact of climatic variability on water-use forecasting is considered. The paper concludes with a graphical comparison of existing water-use forecasts to the years 2000 and 2020 with the results of a simple forecasting model constructed by the authors.

DEFINITION AND USE OF THE TERM “DEMAND”

The concept of a demand schedule in its strictest sense applies only to consumer purchases. Purchases of resources and materials inputs by producers to satisfy the demands of consumers for specific products are more properly termed “derived” demands. The terms “water requirements” or “water use” have been historically associated with water development planning and do not carry any precise or rigorous connotation of quantitative measurement of water withdrawals in relation to price. They are generally used in an engineering or technological context to relate the quantity of water employed in the production process per unit of output.

The use of the term “water demand,” as opposed to “water requirements” or “water use,” carries with it the implication that the impact of price on the amount of water being withdrawn has explicitly been taken into consideration and that the amount being withdrawn is the smallest amount needed for whatever purpose to minimize costs to the withdrawer.

This may be true if the withdrawer is an individual consumer. If, as a matter of policy, prices of public supplies are increased to agricultural and industrial producers, there is no guarantee that they will in fact use less water but in times of inflation may simply pass the increased costs on to the purchasers of their products and ultimately to consumers, adding further upward pressures to market prices. This has been a vexing matter. In the market economies, there has been a continuing search for more precise policy instruments that have greater certainty of achieving a more efficient use of resources than certain autonomous increases in commodity prices.

There is another aspect to the demand for water. Water is demanded for productive uses. There are also overwhelming demands for the waste-assimilation services of water. Pricing policies concerning the latter in the form of taxes and surcharges on pollutants and volume of outfalls have been long recommended. In the United States, events overtook these recommendations in 1972 in the form of amendments to the Federal Water Pollution Control Act, known generally as Public Law 92-500. Under Phase I of the law, federal regulations require industry to install “best practicable control technology currently available” (BPT); Phase II requirements are intended to be more rigorous and more innovative. Industries are to install best available technology economically achievable (BAT) by July 1, 1983, and, ultimately, all point source controls are directed toward achieving the national goal of the elimination of the discharge of pollutants (EOD) by 1985. In the case of irrigation, the Act requires the use of Irrigation Management Services (IMS), in which water use and return water discharges are to be scientifically managed to ensure minimal use and minimal discharge. Under the provisions of Public Law 92-500, revolutionary changes in water use in most sectors can be expected, and the projection of water “demands” should ultimately be subject to some minimal technological requirements in most cases. If the provisions of the Act are enforced in the agricultural and industrial sectors, water demands and water requirements may become essentially equivalent regardless of the withdrawal price of water.

STATE OF THE ART OF FORECASTING DEMANDS

Projections of demands for water are usually made for the major industry divisions and the household (residential) sector of the economy. Traditionally, however, water-use categories and economic-sector categories have not been aligned. Specifically these categories can be listed as shown in Table 3.1.

In order to bring the economic-sector categories into agreement with the Gross National Product and its components for analysis and projection purposes, the additions to the economic sectors shown in Table 3.2 are necessary. This grouping provides an exhaustive, highly aggregated classification scheme for all productive sectors of the national economy or its geographic regions.

The Gross National Product (GNP) is a scalar quantity that is typically projected by federal agencies in constant dollar terms to various target years.[2,3] The projected scalar values can then be decomposed into the sectoral components that reflect the relative growth or decline of these within the overall control total. The resulting estimates can be termed “consistent.” That is, the interdependent nature of the sectors of the economy is usually explicitly (or implicitly) recognized. If the individual sectors were projected on the basis of historical trends or other criteria and the values summed for the target years, results may be inconsistent with more reasonable estimates of the GNP based on the material requirements of the projected population and resource availability. Moreover, since water is regional in its occurrence, the national control

TABLE 3.1 Economic-Sector and Water-Use Categories

Economic Sector		Water Supply-Demand Category	
1.	Agriculture	1.	Irrigation
2.	Mining	2.	Mineral Industry Water Use
3.	Manufacturing	3.	Industrial
4.	Utilities	4.	Thermoelectric Power
5.	Trade and Services	5.	Commercial
6.	Households	6.	Municipal (Part)

totals can be disaggregated spatially to yield a further consistency for the various sectoral components.

TABLE 3.2 Additional Economic-Sector and Water-Use Categories

Economic Sector		Water Supply–Demand Category	
1.	Agriculture	1.	Irrigation
2.	Forestry and Fisheries	2.	—
3.	Mining	3.	Mineral-Industry Water Use
4.	Construction	4.	—
5.	Manufacturing	5.	Industrial
6.	Utilities	6.	Thermoelectric Power
7.	Transportation and Communication	7.	—
8.	Trade and Services	8.	Commercial
9.	Households	9.	Municipal (Part)

Before dealing with the specific sector demand analysis and projections some further points should be made regarding the alignment of water supply–demand categories with the economic-sector categories.

Consistent estimates in money terms can be made for the GNP and its sector components as indicated above. It is desirable that these be matched (aligned) as closely as possible with water-demand estimates in physical terms, i.e., gallons per day or acre-feet per year. This is not an easy problem since the engineers and hydrologists generally charged with the responsibility for gathering or estimating the water data do not choose their classifications to fit precisely with the economic-sector specifications. Water uses may be measured or gauged by the amount supplied in a given time period. Further, water may be impounded and supplied for certain joint uses, and it may not be known except in the most aggregate way which end use actually withdrew the water. For example, water may be impounded and distributed by a public water supply system. The water may be supplied to households, industry, municipal buildings, and commercial enterprises. In fact, multiple-unit dwellings are frequently considered a commercial use of water and are so classified by many water-supply agencies. Thus, commercial and multipleunit dwelling household uses may be inseparable in the supplying agency's records, and other estimating techniques must be found to separate these for analytical purposes. The same type of end-use identification occurs for commercial and industrial uses from time to time. The overall alignment scheme suggested above is not entirely precise but is probably the most satisfactory for establishing aggregate control totals, given the nature of the basic water-use data as presently compiled.

DEMAND ESTIMATING AND FORECASTING TECHNIQUES FOR AGRICULTURAL (IRRIGATION) WATER

The state of the art in estimating demand functions for water used in agriculture appears to be progressing at three levels: (1) the micro, or small area, approach; (2) the macro interregional programming approach; and (3) the dynamic multisector model approach.

Examples of the first approach are cited by Howe[4]:

For consumer goods and many producer inputs, we have data on prices, quantities sold, and other relevant variables sufficient to permit estimation of the demand function. For irrigation water, markets generally don't exist, prices are usually nominal and highly subsidized and unrelated to costs or willingness to pay. Transfers among uses are infrequent and sluggish. Thus, often we simply don't have the data needed to estimate the demand functions for irrigation water. It is then necessary to estimate farmers' willingness to pay for water by modeling their production operations and, upon the assumption that the farmer consciously or unconsciously is attempting to maximize profits, deducing how his applications of water would vary as the price of water is varied. This is most frequently done through linear programming models in which the activities represent different crops and methods of cropping (including different amounts of water). The same results can be deduced by placing a water constraint on production, plotting the relationship between the *shadow price of water and the quantity available.* Examples of excellent studies following this approach to the estimation of irrigation demands are Moore and Hedges,[5] Young and Bredehoeft,[6] Cummings,[7,8] Stults,[9] and Gisser.[10] The resultant demand functions are either for individual farm or farms of different types,[5] for a farming area,[6,7] or for an entire region.[8–10]. . . Other methods are possible for estimating irrigation water demand functions. Hartman and Anderson[11] estimated the value of irrigation water from farm sales data. Anderson[12] has estimated irrigation water values from data on seasonal water rental markets in northeastern Colorado. Gardner *et al.*[13] have estimated irrigation water values from time series data on water rental values before and after consolidation to Utah irrigation districts.

The outstanding example of the second approach is the interregional programming model developed by Heady.[14] The Heady model is formulated as a linear program, the solution of which yields the least-cost distribution of agricultural production by crop type and geographic region, under various assumptions about resource availabilities and their costs, farm support programs, and consumer and export demand for agricultural products. The model was developed to use the following data as inputs. The 223 water-resource subregions defined by the U.S. Water Resources Council are used to specify the basic geographical production areas. In each production area the quantities of land that are available for various types of production are identified. These include crop land, irrigated crop land, dry land for tame hay or crops, irrigated land for tame hay or crops or land available only for pasture or wild hay, and land diverted by certain government programs. Consumptive uses of water for municipal, industrial, and specific on-site purposes (such as wet lands) and for fruit, vegetable, and rice growing are forecast as requirements for each water-supply region. The limitations of water and land serve as the major constraints on agricultural production in each geographical area in the model. Additional constraints reflecting the need for crop rotation and the need for satisfy

TABLE 3.3 Correlative Water-Use Factors

Y	*X*	*n*–2	*r*	r^2	*P*, percent
By river basin					
Total water	Value of production	16	0.58	0.34	2
Total water (except natural gas processing)	Quantity of crude material	16	0.66	0.44	1
New water (except natural gas processing)	Do	16	0.68	0.46	1
Percent total water recirculated	Average temperature	16	0.64	0.41	1
Consumed water	Do	16	0.59	0.35	1
Do	Humidity	16	−0.54	0.29	2
Do	Recirculation	16	0.75	0.56	1
By commodity					
Total water (except natural gas processing)	Quantity of crude material	33	0.62	0.38	1
Percent new water consumed	Percent total water used for cooling and condensing	17	0.69	0.48	1
By states					
Recirculated water	Value of product	43	0.61	0.37	1
Consumed water	Temperature (30-year average)	43	0.43	0.18	1
Do	Temperature (1-year average for 1962)	43	0.43	0.18	1
New water (treated)	Population 1960	48	0.46	0.21	1

TABLE 3.4 Noncorrelative Water-Use Factors

Y	*X*	*n*–2	*r*
By river basin			
New water	Average precipitation	17	0.04
Do	Mean stream discharge	16	−0.01
Recirculated water	Value of production	17	−0.14
Do	Average precipitation	17	−0.10
Do	Mean stream discharge	16	−0.12
Do	Days with 0.01-in. precipitation or more	16	−0.23
Do	Humidity	16	−0.21
Recirculated water (except natural gas processing)	Days with 0.01-in. precipitation or more	16	−0.24
Percent total water recirculated	Do	16	−0.42
Do	Humidity	16	−0.33
Recirculation per ton crushed limestone	Days with 0.01-in. precipitation or more	16	0.52
Recirculation per ton sand and gravel	Do	13	0.35
Consumed water	Precipitation	17	−0.22
By commodity			
Total water	Value of production	33	0.14
Total water per ton	Value per ton	7	0.21
Discharged water per ton	Recirculated water per ton	32	0.21
Water consumed per ton	Do	32	0.25
By States			
New water	Precipitation (30-year average)	43	0.11
Do	Price of water	42	−0.11
Recirculated water	Precipitation (30-year average)	43	−0.03
Do	Price of water	42	−0.04
Consumed water	Precipitation	43	−0.11
New water treated	Population density	48	−0.14

ing basic nutrient requirements in animal feeding are also included. Given the constraints for each producing area, the objective of the model is to find the geographical distribution of agricultural production that satisfies the forecast demand for food and fiber at the national level while at the same time minimizing the cost of agricultural production. By means of a given set of assumptions about price support levels, quantities of land under diversion, export levels, consumer demands, and water prices, the various solutions of the model give the level of production by each agricultural activity, the quantities of water and land used productively, and the marginal values of water and land in use, for each region. The results so obtained have been primarily used to provide indications of relative changes in demand that might be anticipated under alternative futures. In order to evaluate the sensitivity of water use in irrigated agriculture to the price changes of water, the prices of water that are paid by agricultural producers in the model were increased systematically above the prices charged by the Bureau of Reclamation in different water-supply regions. Prices of $15, $22.50, and $40 per acre-foot were evaluated where they were higher than prevailing prices. The findings appear to indicate that the demands for water in the water-short areas of the West could be relatively insensitive to increases in water prices from the prevailing low levels to prices of up to $15 per acre-foot in the water-short areas in the Great Basin, Lower Colorado, Missouri–Arkansas–White–Red, and Texas Gulf. The higher water prices resulted in increased prices for each commodity classification that was studied. If a $40 per acre-foot price of water prevailed, it was estimated that beef prices would be 9 percent higher than they are under present water prices, and the price of wheat was estimated to be 10 percent higher. The ultimate effects of such higher farm product prices on retail food prices were not studied. Given the present inflationary trends, this is a crucial issue that cannot long be overlooked.

An example of the third approach is that of Duloy and Norton,[15] whose efforts form part of a larger study of the Mexican economy sponsored by the Basic Research Center of the World Bank. The largest component of the overall modeling effort is a programming model of the Mexican agricultural sector. Possibly the single most striking feature of the submodel is the detailed manner in which the demand for agricultural products is specified. Not only are demand functions for 33 short-cycle crops included at the national level, but import and export estimates are made for 21 of these crops. Prices for commodities that do not enter foreign trade are determined endogenously, and prices for traded commodities are bounded both above and below by Mexican FOB and CIF prices. The model functions as a market-clearing general-equilibrium system in respect to agricultural commodity production. Duloy and Norton were able to include within their linear programming format both a competitive and noncompetitive market equilibrium. Agricultural markets have typically been competitive; however, the incomes accruing to agricultural enterprises under major changes in output may respond like the incomes that would be experienced by any monopolistic producer. Thus, while agricultural markets are usually characterized by competitive conditions, future national policy may require that some constraints be imposed in this area.

WATER DEMANDS IN THE MINERAL INDUSTRIES

Water needs of the mineral industries constitute only about 2 percent of water withdrawn by the industrial sector as a whole.[16,17] The largest water-using mineral industries are natural gas processing, phosphate rock, sand and gravel, and iron ore.

Kaufman and Nadler carefully analyzed the results of a comprehensive canvass of mineral-industry water use in 1963. This analysis was based on the product–moment method of calculating correlation coefficients.

The results are presented as Tables 3.3 and 3.4; r^2 is the coefficient of determination, and P is the level of significance. From Table 3.3 it can be seen that approximately 44 percent of the variation in total water use can be explained by the amount of crude material that was processed.

Kaufman and Nadler further state[16]:

Some 46 percent of the variations in new-water use can be explained by variations in crude material. The remaining 54 percent is assumed to be the result of processing variations.

As total water use is the sum of new and recirculated water, the bulk of the effort in the correlation analysis was devoted to these components rather than to the total. This analysis indicated that water availability, as measured by average precipitation or mean stream discharge, is not a use factor insofar as new-water use by the mineral industry is concerned. There does not appear to be a relationship between new-water use and the price of water, although the lack of relationship may result from the type of price data used. The price of water was taken from charges levied by water companies against large industrial users in selected cities for 1955.[18] However, most mineral producers obtain their water from self-operated systems, and therefore the type of cost data used may be completely inapplicable. It is also possible that in many cases the cost of water per ton of ore is such a minor item that cost is not a factor in determining use. In other instances the capital cost of developing a self-operated system is so great, compared with the operating cost, that the total cost per gallon will decline substantially the more water is used. The relative low cost of self-supplied water, particularly in relation to purchased water, is substantiated by data compiled by the National Association of Manufacturers.[19] The Association computed that water derived from self-supplied systems would cost between one cent and fifteen cents per 1000 gallons. This would include sources, pumping, treatment and distribution. Water purchased from a utility company would cost between ten and thirty cents per 1000 gallons, exclusive of distribution within the plant.

The authors further point out that if it can be assumed that mineral producers are paying $0.15 per 1000 gallons of water, the cost of water as a percentage of the average values per ton of ore would be as follows:

	New Water (%)	Total Water (%)
Bituminous coal	0.3	1.8
Copper ores	1.3	3.0
Iron ores	1.2	2.7
Phosphate rock	3.9	13.0
Sand and gravel	4.3	6.7

The figures shown can be considered to be maximums, since many mineral producers do not pay $0.15 per 1000 gallons. Except for the very large user such as the phosphate rock industry, or an extremely low-value product such as sand and gravel, the cost of water cannot be seen as a significant item. A general assumption can be made that the cost of recirculated water is lower than the cost of new water. Therefore the proportion of average value contributed by total water costs is most likely to be less than indicated by the foregoing data. This tends to bear out the lack of statistical correlation between water intake and prices. From the foregoing it can be inferred that statistical demand functions for water, as they are generally understood, essentially do not exist for the mineral industry.

INDUSTRIAL WATER DEMANDS

The factors affecting industrial water demands for a number of industries have been dealt with in some detail by Bower.[20,21] Bower formulates conceptually a joint function governing industrial water demand as follows:

$$Q_{It}, Q_{Dt}, C_t, Q_{Et}, W_{Dt}, W_{Et} =$$

$$f(Q_t, q_t, T, PP, L, OR, poqr, R, S, E_c, A_c, Q_{dt}, q_{dt}, D, c_w/c_t),$$

where

Q_t and q_t	are the quantity and quality and their corresponding time patterns of water available at the intake;
T	is the water- and waste-treatment processes within the production unit;
PP	is the technology of the production process;
L	is the physical layout of the plant;
OR	is the operating rate;
$poqr$	is the product output quality requirements;
R	is the degree of recirculation;
S	is the solid wastes from the production process;
E_c	is the limitations on the final liquid effluent;
A_c	is the limitations on the final gaseous effluent;
Q_{dt} and q_{dt}	are the quantity and quality and their corresponding time patterns of water available for dilution at the effluent point;
D	is the availability of places for final disposal of wastes; and
c_u/c_t	is the ratio of total water utilization costs to total production costs.

Bower emphasizes that a forecast of industrial water demand for a particular industry must include the amount of water required for all uses explicitly—process, boiler feed, cooling and condensing, and sanitary uses. Because of increasing concern over thermal pollution, a separate consideration of cooling and condensing uses is stressed. These include product cooling, equipment cooling, and condensing in steam electric power generation.

Bower summarizes[20]:

Essential to any effort to forecast industrial water demand is an economic base study which includes projections of demands for the product outputs of the various heavy water-using industries. . . . Given an economic base study, forecasting industrial water demand involves the following five steps:

(1) Classifying existing plants by process, region, product mix, and size;
(2) Forecasting trends and production processes, product mix, and regional location patterns, *i.e.,* forecasting technology;
(3) Relating the production process–product mix combinations to gross water applied and waste loads generated;
(4) Analyzing the alternative internal water utilization patterns and costs thereof, considering the impacts of in-plant water quality requirements in relation to product quality and the costs of other factor inputs such as fuel and heat exchanges; and
(5) Forecasting political decisions relating to pricing policy for water at the intakes and policies relating to waste discharges. Given (3) and (4), and the water environment (5), water demand can then be forecast.

In view of the waste-assimilation properties of water, the effect of waste-discharge control on water intake should also be stressed in industrial water-demand forecasting.

Russell, using mathematical programming techniques, developed a model of typical refinery operations that could portray the withdrawal demand for water as a function of intake price and also effluent charges.[22] The National Water Commission staff summarized the results of the Russell model as follows:

1. A petroleum refinery's water withdrawals are sensitive to the price of withdrawals and may be reduced by as much as 95 percent if the withdrawal charge goes above 2 cents per 1000 gallons. If the price is raised further, the refinery will be able to reduce water withdrawal further by in-plant recirculation.
2. Discharges of biological oxygen demand (BOD) materials by petroleum refineries are sensitive to effluent charges. An effluent charge of about 2 cents per pound of BOD material discharged may be approximately the tax that would induce a BOD waste reduction of 50–65 percent, depending on the technology of the plant.
3. The costs incurred by the petroleum refinery (and presumably passed on to the consumer) for reducing discharges of BOD material are comparable with the costs of developing sufficient additional flow to dilute the discharges.
4. The overall effect of BOD effluent standards on the

final gasoline price at the refinery might be about one fiftieth of a cent per gallon.

5. Effluent charges or standards directed at curbing the discharge of one type of residual, or pollutant, could have important effects on the discharge of other wastes. In a refinery of the type studied, the quantities of phenols discharged would also be reduced as the discharge of BOD wastes is reduced in response to a BOD discharge tax.

Although these results imply that petroleum refineries are sensitive to intake water prices and effluent charges, the *1972 Census of Manufactures* (1973 data)[23] shows that refinery intake from all sources was 1278 billion gallons with 635 billion being freshwater. Of this amount of freshwater, 132 billion gallons, or 21 percent, was from public supplies with the balance being self-supplied. Data on effluents show that refineries discharged 1155 billion gallons of water during the year, of which 463 billion gallons, or 40 percent, were untreated.

Refineries are undoubtedly sensitive to the price of withdrawals given the fact that they can and do supply their own needs well below one cent per 1000 gallons as estimated in the National Association of Manufacturers.[24] As the price of publicly supplied water is increased they may opt for developing their own systems. This helps to explain the problem of “block pricing” as noted by Bower[25]:

> . . . it should be noted that in many cases rate structures for industrial water users encourage high water intake per unit of product. Generally, large consumers receive lower rates for using more water—*i.e.,* the more water used, the lower the price per 1000 gallons. In such situations it often becomes less expensive for the industrial user to discharge once used water than to adopt recirculation.

As matters stand, there appears to be no clear-cut method of empirically deriving and projecting demand functions for industrial water use. In contrast to agriculture, reliance on water prices and pricing policies for both withdrawals and discharges seems to have been too tenuous an instrument for achieving the desired goal of dramatically reducing water demands and wastewater discharges. Only 11 percent of industrial water in 1973 was publicly supplied and thus subject to price increases as a matter of policy. This is in contrast to the 50 percent of industrial water drawn from public supplies in 1950.[26] Furthermore, only 60 percent of discharges were treated in 1973. The requirement of Public Law 92-500 can be expected to bring more dramatic changes to industrial water demands than have been evident over the past few decades.

Historical water intake data are given in Table 3.5.

The National Commission on Water Quality report states[27]:

> Several technological solutions for both 1977 and 1983 limitations are founded upon reduction in *water use* or *by-product recovery.* These options are likely to have wider application for BAT [best available technology] than for BPT [best practicable technology]. The full potential for such approaches is undeveloped, but they will probably become more prevalent as limitations become more stringent and technologies for treating large wastewater volumes become more expensive.

TABLE 3.5 Historical Gross and Intake Water Usage by All Manufacturing Industriesa

Year	Gross Water Used (billions of gallons)	Net Water Intake(billions of gallons)
1959	26,257	12,131
1964	29,857	14,007
1968	35,701	15,467
1973	46,965	15,024

In general, the Commission on Water Quality submits the data in Figure 3.1 to show overall industry responsiveness to price changes in water and cost increases in waste discharge.

The price elasticity of demand for industrial water intake as given can be used as a guide for estimating future withdrawal demands in limited instances.

THERMOELECTRIC POWER WATER DEMAND

Steam electric generating stations primarily use water for cooling. The amount of cooling water withdrawn per kilowatt-hour generated is governed by the type of plant, the thermal efficiency, the number of degrees over which the intake water is heated (this is termed the “range”), and the method of cooling that is used. The amount of water used in steam electric power generation in the United States is now greater than irrigation water withdrawals.[28] It accounts for somewhat more than 40 percent of all water withdrawn. Water used consumptively, that is evaporated or lost in the cooling process, is only about 1 percent of total intake at the present time.

A typical “range” for a plant using once-through cooling is 15°F. This means that each gallon used absorbs 125 Btu of waste heat.[29] On this basis, some 43 gallons of cooling water are circulated per kilowatt-hour generated in thermal plants, and about one half gallon (1 percent) of this water is ultimately evaporated.[30]

Table 3.6 provides estimates of water withdrawals and consumption for the years 1980–2020 for thermal electric generating facilities.[31] These estimates assume minimal increases in plant efficiency and once-through cooling practice. The assumptions, although termed unrealistic by the National Water Commission staff, afford an upper bound for withdrawal and consumptive uses based on projected growth of thermal generating facilities. The values shown in the table indicate that the withdrawal needs for condenser cooling will be approximately equal to the average annual runoff of the United States by the year 2000. The consumptive use is only slightly more than 1 percent of withdrawals, however.

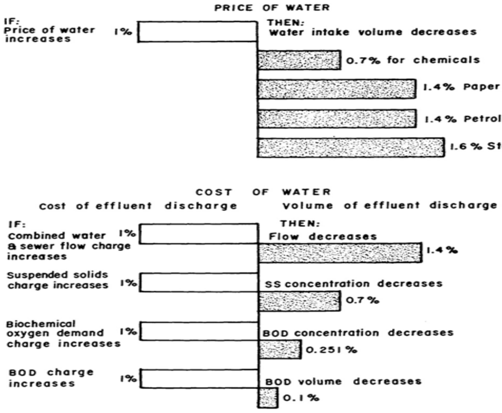

FIGURE 3.1 Industry responsiveness to cost of intake water and waste discharge.

In order to place the projected thermal energy demands in perspective and assess some overall means of bringing the associated water needs into balance with available supplies, two avenues have been investigated: (1) the reduction in overall electrical energy demand and (2) the means for the direct reduction in water withdrawals.

(1) An analysis of socioeconomic data for the period 1955–1969 indicates that electric power consumption plus losses and in-plant uses can be statistically correlated with population, Gross National Product, electricity prices, and gas prices.[32]

The Bureau of Economic Analysis, United States Department of Commerce, has made high, medium, and low projections of Gross National Product to the target year 2020. These were based on the B, C, and D population growth rates of the Bureau of the Census.[33] These growth rates were then used in a regression model to project electric power needs. A fourth projection was based on a low growth rate combined with a 50 percent increase in electricity prices. The four resulting projections of cooling water are presented in Figure 3.2. These projections of freshwater withdrawals assume no technological change and no recirculation.

TABLE 3.6 Sample Projections of Total Water Withdrawals and Consumption for Thermal Electricity Generation (billion gallons per day)

	1980	2000	2020
Withdrawn	330	1072	2297
Consumed	3.8	12.5	26.7

The relation between the price of electricity and cooling-water withdrawals has also been studied. The analysis showed that a 50 percent increase in the price of electricity would result in a 27 percent decline in cooling-water withdrawals. There appears to be some indication that the demand for electricity is related negatively to increases in price. An analysis by Wilson[34] shows that regional power demands may have an elasticity greater than 2, which would mean that a 10 percent increase in price would cause a 20 percent fall in energy use. It is felt that some of this decline would be due to the relocation of energy-intensive industries to other areas where energy rates may be lower. On such evidence, it appears that pricing policies could be used to influence electricity use and thus cooling-water use.

The analysis, however, does not distinguish between the industry demands and consumer demands. In fact, energy studies at the Center for Advanced Computation, University of Illinois, have shown that approximately 65 percent of all energy demands are interindustry demands. For electrical energy only, the proportion may be closer to 55 percent in interindustry demands.[35] If estimates of

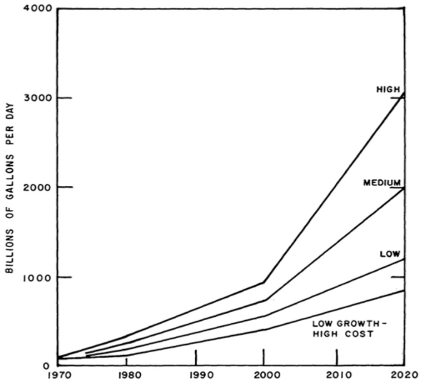

FIGURE 3.2 Projections of freshwater withdrawals for electricity generation under different economic growth rates.

reductions in electricity demand are calculated in such an aggregate manner, the possibilities for "self-supplied" electrical energy are masked. An important problem raised by the research staff of the Electric Power Research Institute relates to the setting of power prices so that large users will continue to purchase "blocks" from utilities rather than develop their own generating capacity—an option available to a number of industries. The foregoing analysis gives no indication which sector (industrial or household) of the economy is affected and the manner in which the reductions may occur.

(2) A potential way to reduce cooling-water withdrawals might be to raise the price of water itself. However, if the price of cooling water is increased, utilities may recirculate the cooling water several times rather than use a "once-through" cooling process. If this is done, then the temperature of the cooling water is raised and evaporative (consumptive) losses are substantially greater.[36] Less water is returned to the natural water course for other downstream users, and thermal pollution problems are increased. Thus, increasing the price of cooling water may result in changing withdrawal demands into consumptive demands and an overall depletion of available supplies in a given period.

It is conceivable that different prices might be levied for withdrawing freshwater and also for using it consumptively. Basically, in order to keep the consumptive use of water at low levels, the only possible alternatives are to use once-through cooling or, at higher water prices, to use dry towers.[36] However, the National Water Commission staff estimated that water prices greater than $1400 per million gallons *consumed* would have to be charged to induce plants to limit their water consumption to the zero level, given the capital cost of dry tower technology.

In the overall, freshwater withdrawals by steam-electric generating stations might be influenced by setting water prices at levels that could only be considered unreasonable in the present economy. The consumptive use of water by thermal plants appears to be insensitive to price changes within what might be considered a reasonable price range. It should be stressed, nevertheless, that pricing withdrawals of freshwater for thermal plant cooling has not yet been tried and may be limited in practice. The response of regulated utility companies to increases in costs is very different from the response of nonregulated industries. Thus, changes in the price of water may in fact have little or no effect on demand. The consumptive use of freshwater for cooling is virtually insensitive to price changes for water within any realistic price range.

COMMERCIAL DEMANDS FOR WATER

The definition of commercial water use by water-supply agencies is probably less rigorous than for any other category. In the alignment scheme presented earlier in this paper in Table 3.2, the commercial sector can be accurately defined as Standard Industrial Classification (SIC) groups 50 through 89, excluding major group 88—Private Households.[37]

Demand functions for water use in the trade and service sectors of the economy are needed; however, only rather fragmentary data appear to have been accumulated and analyzed. Howe reported on these in 1968.[38] One of the points not dealt with by Howe, but mentioned in an earlier section of the present paper, is the fact that many water-supply agencies may classify multiple-unit dwellings as commercial users. Thus, the water supply to apartment houses that are clearly residential or household in nature may be classified as a commercial end-use by the agency. This may tend to skew badly the results of any study. Moreover, many trade and service establishments have the option of self-supplied water systems, which may further tend to limit the validity of the results based solely on an analysis of water-agency data, which reflect supplies to a broad category of users termed "commercial." For analytical purposes, overall water-agency data from selected cities may need to be modified in order to account for the total amount of household intake and the possible misclassification of light industry or other manufacturing establishments to the category of commercial users.

At present, specific price elasticity of demand functions for water used in the various trade and service sectors of the U.S. economy have not been estimated.

HOUSEHOLD (RESIDENTIAL) WATER DEMANDS

Water withdrawals for household use in 1975 amounted to approximately 23.6 billion gallons per day, of which about 91 percent, or 21.5 billion gallons per day, were furnished by municipal water systems.[17] Household water needs are typically divided into two categories: in-house uses and lawn sprinkling. The major in-house uses are drinking and cooking, 5 percent; dishwashing and laundry, 20 percent; bathing and personal use, 30 percent; toilet flushing, 45 percent.[39] For single-family dwellings, lawn-sprinkling uses amount to more than 50 percent of the total yearly use. Howe and Linaweaver statistically analyzed the effects of density, property value, geographical location, and water price on household demands.[40] Both in-house and lawn-sprinkling uses have been found to be responsive to changes in water prices. Table 3.7 shows average commercial water-use data in metered and flat-rate areas.[39]

Howe and Linaweaver determined the important variables governing water use for sprinkling in areas that are metered were water price, dwelling unit value, and precipitation. For flat-rate areas, the governing variable was dwelling unit value. Demands for in-house uses were determined to be less responsive to price and income changes than those for sprinkling.

Using the Howe and Linaweaver data, a Resources for the Future report for the National Water Commission projected household needs to 1990.[40] Under different assumptions of price and population growth, it was argued that the growth of population alone has a greater impact on water use than the spatial expansion of urban areas, and further, the price of water has a much greater impact than either of the two preceding variables.

TABLE 3.7 Average Annual Water Use in Metered and Flat-Rate Areas

	Gal/day per Dwelling Unit	
	Metered Areas	Flat-Rate Areas
Leakage	25	36
In-house	247	236
Sprinkling	186	420
TOTAL	458	692
Maximum Day	979	2354
Peak Hour	2481	5170

In summarizing, it can be noted that the theory of consumer demand truly comes into its own in the analysis of residential water use. The demand functions were well behaved in all cases studied. The data indicate that lawn sprinkling accounts for more than 50 percent of average annual use for single-family dwellings. The amount of sprinkling water used decreases with price increases. This is less striking in the western United States than in the East. The amount of water used for in-house purposes is approximately the same regardless of the price charged for the water.

USE OF DEMAND FUNCTIONS IN WATER-RESOURCES SYSTEMS PLANNING

The term “water-resources systems” can be used to encompass the large-scale impoundments and conveyance systems typical of the Tennessee Valley Authority and the Bonneville Power Administration and the smaller pumping, storage, and distribution systems of many metropolitan areas. Historically, in the United States many of these systems were developed on the basis of engineering feasibility studies and certain multipurpose objectives, such as hydro power generation, flood control, land reclamation, and navigation, along with water supply. Many of the nation's largest multipurpose water-resource systems were planned and developed after 1930 when the federal government indirectly assumed an increased responsibility for the use of water resources. Most, if not all, of these large projects were begun as part of the major public works programs typical of the 1930's.[41] Several decades earlier, the Reclamation Act of 1902 had been passed to stimulate and consolidate the westward expansion that followed the development of the transcontinental rail lines. By 1929, about 19 million acres were irrigated,[42] although only about 7.5 percent were directly controlled by the Bureau of Reclamation.

At present, attention is focused on the rather striking amounts of water that have been developed by means of federal projects, the rather modest prices that are charged for water, and what the past trend augurs for the future. It is felt that if water prices are permitted to rise on the basis of the value the water would have in alternative uses, or are increased as a matter of public policy, then users would presumably carefully monitor their withdrawals to minimize costs and thus substantially reduce overall water use in the economy. If this occurs, new projects can be postponed or possibly deferred indefinitely. This would permit substantial sums of money, tentatively allocated to proposed projects, to be reallocated to other pressing national needs. These considerations are obviously at the root of the demand versus requirements issue.

In the earlier sections of this paper, the potential for developing statistical demand curves for each major category of water use was explored. In light of the findings, it seems feasible that water-demand functions for irrigation water can be developed, using either statistical analysis or mathematical programming techniques, and applied in water-resources systems planning. For the mineral industries and certain industries that are heavy users of water, the prospects for developing and using statistical demand functions in systems planning appear to have been overshadowed by changes in the Water Pollution Control Act passed by Congress in 1972. The stipulations of the Act will bring to the fore some minimal technological level of water use to meet discharge standards regardless of intake price. The best achievable technology (BAT) should carry with it some minimal level of in-plant use of water for all industries. If the provisions of the Act are enforced, water price should have little influence on demand in the future for those classes of industries that have traditionally been termed “water intensive.”

For the trade and service sectors and those light industries where water use is limited to sanitary, air conditioning, and boiler feed uses, and certainly for residential and household needs, the development and use of water-demand functions should play a major role in water-resource systems planning in the future. Such applications will probably find more immediate use in the planning of metropolitan water-supply systems than in any large multipurpose project in which water supply is coupled with flood protection or other water-related considerations.

THE ROLE OF WATER-USE INFORMATION IN FORECASTING FUTURE WATER DEMANDS

Official water-use data are compiled and published by several federal agencies. Additionally, there are special studies funded by federal, state, and local governments as needs arise.

Official data sources:

1. United States Geological Survey, "Estimated Use of Water in the United States," quinquennially since 1950.[28,43 –46]
2. United States Water Resources Council. National Water Assessment Studies, by decades beginning in 1965.[17,47]
3. Census of Agriculture, United States Bureau of the Census. Irrigation and Drainage on Farms.[48]
4. Census of Mineral Industries, United States Bureau of the Census. "Water Use in Mineral Industries," Economic Census years 1954, 1963, 1967, 1972.[49 –52]
5. Census of Manufactures, United States Bureau of the Census. Water Use in Manufacturing. Economic Census years 1954, 1958, 1964, 1968, 1973.[53 –57]
6. United States Army Engineers Permit data, 1971, unpublished.[58]

The United States Geological Survey (USGS) data provide water use by major categories for the United States, the 50 states, and water-use regions. The data are related to population and acreage. A bibliography of primary data sources is given in the USGS publications.

The United States Water Resources Council provides base-year data, principally following the USGS categories, and furnishes projections at 10-, 15-, or 20-year intervals. The data as presented are not related to measures of production.

The Census of Agriculture includes data on drainage basins, land irrigated, crop production on irrigated land, water conveyed, users, and types of organizations.

The Census of Mineral Industries and Census of Manufactures water data are furnished for detailed categories of end-use and are related to establishment, employment, value added, and value of shipments for the United States, the 50 states, and regions. The Army Engineers Permit data relate water use to employment and value of product for specific dischargers.

At the state and regional levels, the Census data become sketchy because of disclosure problems; however, they can be made usable with some statistical effort.

As resource scarcities, particularly water, have become increasingly evident in the United States, the need for estimating future demands in some standardized manner has been apparent. The sources of supply are regional in nature, as are the elements of demand. If forecasting techniques are not standard and uniformly applicable to any of various geographical regions, estimates of supply and demand may tend to embody broader interregional political considerations rather than the objective realities of regional resource availabilities. Water-resource development, transfer, and distribution systems are usually capital-intensive and may take as long as a quarter of a century from conception to water delivery for major projects. Over the decades, this has led planners to perhaps wish to err on the side of recommending excessive refinement in projection techniques rather than be guilty of overbuilding. If, of course, it can be successfully argued that the benefit–cost ratio of obtaining better data for planning purposes at any level is not greater than one, then the concern over detail is not a valid one. Nonetheless, the dilemma for planners is real. If they are conservative in planning irrigation projects, the basic objective of adequate food supplies is defeated by shortfalls in production and high prices. If they are liberal in their projections, unused facilities and surplus productive capacity bring on not only agriculture surplus problems but also a loss of public confidence.

In order to project future water demands in a standardized fashion for a region, a series of regions, and ultimately the nation, a multisector economic framework should be established for some base year. Such a framework permits region-by-region comparisons to be made objectively. Economic activity projections can be made by region in constant dollar terms to the specified target years from the base year. The finer the industry detail, and the water-use detail available by specific purpose for the base year, the more comfortable one might feel that errors might tend to be in a conservative direction. As the time span of the projection is increased, the likelihood lessens for a detailed product mix or perhaps even the industry mix to be maintained in any specified proportions for a given economic region. Projections, of necessity, have to be made in a more aggregate format as the time span from the base year increases. Once the given set of industry projections in constant dollars has been made, the base-year water-use information can be modified in the light of modeling techniques that include demand elasticity considerations, where they are applicable, and technological considerations for those sectors where these seem to be the governing factor, i.e., where thermoelectric cooling may be involved.

The base-year water-use information should also include data on self-supplied or publicly supplied water. Consideration should be given in the economic projections to the practice the various industries in the region will be expected to follow in regard to sources of supply throughout the time span under consideration. When dealing with economic variables, there tends to be a certain stability exhibited by aggregates and their projection despite marked changes in their underlying components. A relevant example that can be cited is the water-use forecasts made by the staff of the Paley Commission in 1952[26] shown in Table 3.8. Based on the water-use information available in 1950, a forecast of requirements for 1975 was made. The estimate for 1975 was some 4 percent lower than the 1975 figures provided by the United States Water Resources Council,[17] despite substantial changes in product output beyond those forecast in detail by the Commission.

Although the period 1975 to 1985 should bring major changes in the pattern of water use, once new technology is adopted, it is reasonable to speculate that longer-term projections of the rate of growth of withdrawal demand may stabilize at some markedly lower intake value. Because of recirculation and reuse, consumptive demands may rise substantially during the same period.

TABLE 3.8 Estimated Total Withdrawals and Requirements for Water 1950 and 1975

	Estimated withdrawals, 1950		Estimated Requirements, 1975		Increase, 1950–1975	
	Billion Gallons per Day	Percent of Total	Billion Gallons per Day	Percent of Total	Billion Gallons per Day	Percent Increase
Municipal and rural[a]	17	9	25	7	8	50
Direct industrial	80[b]	43	215	62	135	170
Irrigation	88	48	110	31	22	25
TOTAL	185	100	350	100	165	245

[a] Roughly half of total municipal supplies are used industrially.

[b] Includes an estimated 15 billion gallons per day of salt water used in industry for cooling.

In earlier sections of this paper it has been noted that demand functions can be estimated statistically for most consumer goods. It has also been pointed out that large-scale multisector programming models have been used in certain instances to estimate demand functions for water for the agricultural and industrial sectors of the economy. Given the marked changes in water use that may occur in various sectors under the stimulus of water-pollution control measures, it seems unlikely that a high degree of reliability should be attached to demand functions for water based on current data. For the agricultural and industrial sectors of the economy, the forecasting of future water demands may be greatly improved by implementing a series of detailed process analysis studies to determine the required minimum amounts of water that will be necessary for these sectors to function efficiently under adverse conditions. Placing too great a reliance on the concept of market supply and demand functions as opposed to gaining a comprehensive understanding of the technological possibilities for reducing resource inputs may be an error. The entire discussion of deriving market supply and demand functions should be leavened with the critical comments of some detractors. Leontief[59] has given some insight into the problems relating to the derivation of demand functions:

As objects of empirical analysis the market supply and demand functions [have] proved to be singularly elusive. They cannot be observed directly and most attempts to derive them through methods of indirect statistical inference have yielded—with a few notable exceptions—disappointing results. The principal difficulty lies in the great instability of the observed price– quantity relationships and this instability can be shown to be inherent in the internal logic of the general equilibrium system itself. Within the framework of such a system each structural relationship is by definition independent of all the (structural or non-structural) relationships. Every price and every quantity produced or consumed is on the contrary—by the theoretical general equilibrium hypothesis—expected to depend simultaneously on all the structural relationships. This means that, if the hypothesis as applied to an observed system is correct, the dependent variations of each price and quantity would necessarily reflect the autonomous changes of all the basic structural relationships and, what is more important, these variations will be distributed in such a way that a statistical determination of the unknown shapes of the corresponding Walrasian demand and supply equations would practically be impossible.

Boulding and Spivey have spoken to the same problem within the broader framework of the theory of the firm[60]:

A theory which assumes knowledge of what cannot be known is clearly defective as a guide to actual behavior. What must be known, however, . . . is a whole set of functional relationships, such as demand and supply functions, which are *not* given by immediate experience, and often are not even given by the most refined analysis of past data.

Theoretical demand functions for the industrial sector should thus be seen as useful heuristic devices. For empirical research they provide an overall framework for structuring the various components of water-use information.

IMPACT OF CLIMATIC VARIABILITY AND CHANGE TO FORECASTING DEMANDS

Currently there appears to be no firm consensus regarding the magnitude or direction of future climatic change. There is geological evidence that such changes could occur relatively rapidly—50 to 100 years—and that the impacts might possibly have catastrophic consequences in terms of human conditions.[61]

Translating the impacts of climatic variability and change into certain direct effects on regional and national water demands can, at best, involve only the grossest assumptions as matters stand.

A general warming trend in the United States climate could translate into increases in evaporative losses, lowered efficiencies in cooling for all major purposes, increased use of water for air conditioning, and presumably some decreases in boiler feed water for heating. If a general cooling trend were to be experienced, then evaporative losses would be decreased, cooling efficiencies may be increased slightly, air-conditioning uses would decline, and boiler feed-water use should increase. Quantifying these changes in response to the expected climatic changes would require a detailed modeling effort.

The impacts of climatic variability in terms of worldwide and local droughts will have both direct and indirect impacts on U.S. agriculture, which may overwhelm the other aspects of water-demand changes. Winstanley *et al.,*[62] Winski,[63] and Alexander[64] summarize predictions that indicate that by the year 2000 the prevention of starvation may be the main global concern. This view is not by any means entirely acceptable to many agriculturalists or water planners. On balance, agriculturalists have acknowledged this possibility; however, in the face of past agricultural surpluses in the United States it has not been considered a fruitful avenue of research. One can cite, for example, the typical comments in a text by Barlowe[65]:

Winstanley *et al.*[62] state, nevertheless:

Probably the most serious problem facing the world concerns our ability to meet the increasing demand for food. At least one and a half billion people are chronically mal-nourished (Erlich and Erlich 1972)[66] and it has been estimated that 10-20 million people die every year directly or indirectly from lack of food (Dumont and Rosier 1969).[67] These figures are for an average year, and do not reflect the situation in times of drought or other calamities (U.N. 1974).[68] Last year some ten million people in the Sahel Zone of Africa were on the brink of starvation, and 100,000 people in Ethiopia died from starvation. Hunger is closely correlated with poverty and both lead to social and political instability: within the last twelve months there have been political upheavals in the drought-affected countries of Ethiopia, Upper Volta, and Niger, and serious food riots in India. Food production must be doubled in about thirty years to meet the projected demand—and it has taken at least ten thousand years to attain the present level of production.

The U.N. (1974)[68] has identified the effect of recent adverse weather conditions on crop production as one of the major factors in the present world food crisis. World grain reserves now represent less than a month's food supply for the world and there is no longer any idle agricultural land in the U. S. A. to act as a reserve. There is a real threat that crop failures would lead to widespread starvation.

Evidence is accumulating which shows that the climates of the Earth are changing, and it has been suggested that they might be changing in a direction which could have a net adverse effect on world food production, and global economic and political stability (I.F.I.A.S. 1974[69]; Rockefeller Foundation 1974[70]).

Probably the main reason for irrigating and draining the land is to increase food production and one of the main factors determining the need for irrigation and drainage is climate.

If the Winstanley, Alexander, and Winski summary prospects are borne out, then planners may possibly have to reconsider the extent to which irrigable lands will play a preponderant role in the future, and present projections may have to be revised. Alexander cites Reid Bryson, who contends that the monsoons may probably not return with regularity to regions such as northern India during the remainder of this century. If this is correct, the prospect looms that even the present populations of the monsoon belts could not be maintained even if all the arable land in the rest of the world were placed in full production for this period. Because of the unusual and irregular way in which the global weather changes are beginning to manifest themselves, there is some evidence that a return of heavier rainfall in the western plains and Rocky Mountain states may not be unusual. Settlers who traveled to California left accounts that one of the hazards of crossing the plains was the possibility of losing sight of the main party because of endless stretches of head-high grass that grew in regions that are almost desert at the present time. Bryson speculates that the change in climate might possibly have played a greater role than hunters in the disappearance of the huge herds of bison. If the heavier rainfalls in the western United States were to occur, then possibly certain proposed irrigation projects might have major flood-control benefits.

On the other hand, Winstanley has noted that if the weather patterns in Africa persist they may shift the entire Sahara Desert southward; and efforts to halt such climatological encroachments by, for example, planting windbreaks or increasing irrigation would be in vain. In the Soviet Union, for example, a third of the grain crop comes from the drought-prone virgin lands of Siberia, and consideration has been given to diverting some of the great Siberian rivers into large irrigation projects. These rivers empty into the Arctic Ocean, where the less-dense freshwater spreads out on top of the salt water and thus permits the Arctic Ocean to freeze over. According to some experiments by a Russian scientist, O. A. Drozdov, and a British meteorologist, R. L. Newson, who have constructed a mathematical model of wind patterns in the northern hemisphere, the consequence of inhibiting the freezing of the Arctic Ocean may be to cause winters to become colder and drier over many continental areas at the middle latitudes. Some prominent Soviet meteorologists have expressed concern over these proposals. However, if disastrous, protracted droughts were to occur in the Siberian wheatlands, Soviet planning authorities might feel that there would be little to lose in proceeding with these projects. In the United States and Canada such proposals as the North American Water and Power Alliance schemes called for diverting rivers like the MacKenzie, which flows northward into the Arctic Ocean and through large impoundment and conveyance structures carrying these waters southward into the United States for irrigation and power-generating purposes. Such engineering schemes could possibly have impacts similar to those of the proposed diversions in the Soviet Union. If droughts were to persist, possibly these schemes, or some variant, might be given consideration in order to increase worldwide food supplies.

In order to place the question of increased irrigation demands in perspective, assuming that increased food production requires this, land-use patterns and trends are given for the United States (Table 3.9). Irrigated acreage data are given in Table 3.10. It should be noted that these data are provided for the 17 western states only. Federal irrigation projects data are provided in Table 3.11.

TABLE 3.9 Land Utilization, Farm and Nonfarm: 1940-1969 (in millions of acres, except percent). Prior to 1950, excludes Alaska and Hawaii[a]

	1940		1950		1959		1964		1969	
Major Use	Land	Percent	Land	Percent	Land	Percent	Land	Percent	Land	Percent
Total land area	1905	100.0	2273	100.0	2271	100.0	2266	100.0	2264	100.0
In farms	1061	55.7	1162	51.1	1124	49.5	1110	49.0	1064	47.0
Cropland[b]	399	20.9	409	18.0	392	17.3	387	17.1	384	17.0
Grassland pasture[c]	461	24.2	486	21.4	532	23.4	547	24.1	540	23.9
Woodland pastured	100	5.2	135	5.9	93	4.1	82	3.6	62	2.7
Woodland not pastured	57	3.0	86	3.8	70	3.1	64	2.8	50	2.2
Farmsteads, roads, and other land	44	2.3	46	2.0	37	1.6	30	1.3	28	1.2
Not in farms	844	44.3	1111	48.9	1147	50.5	1156	51.0	1200	53.0
Grazing land[d]	504	26.4	402	17.7	319	14.0	293	12.9	288	12.7
Forest land not grazed[e]	203	10.7	368	16.2	438	19.3	443	19.5	475	21.0
Other land[f]	137	7.2	341	15.0	390	17.2	420	18.5	437	19.3

[a] Source: U.S. Dept. of Agriculture, Economic Research Service. In *Agricultural Statistics,* annual.

[b] Comprises cropland used for crops, soil improvement crops, and idle cropland.

[c] Includes cropland used only for pasture.

[d] Includes grassland, arid woodland, and shrub and other forested land grazed.

[e] Excludes forest areas in parks and most other special uses.

[f] Comprises urban, industrial, and residential areas; rural parks; wildlife refuges; highway, road, and railroad rights-of-way; ungrazed desert; rocky, barren, swamp, tundra, and other land not otherwise counted.

In April 1974, the Water Resources Council released the new Series E Population OBERS projections showing an 18 percent decrease in cropland harvested by the year 2020 (Table 3.12). In May 1975, a revised series of agricultural projections (Series E') was released, which showed a 15 percent increase in cropland harvested by the year 2020 (Table 3.13). The revisions have been attributed to more recent assessments of the domestic and foreign supply-demand relationships.

Figure 3.3 has been reproduced from Winstanley *et. al.*[62] If the United States should wish to assume a posture in which the food deficits of the so-called "Third World" countries can be met by the agricultural production of the United States and other developed countries, then further revisions of the projections of irrigated cropland may be in order.

WATER-USE FORECASTS FOR 2000 AND 2020

Projections of water withdrawals and consumptive use to the years 2000 and 2020 were made by the United States Water Resources Council in 1968[47] and by Wollman and

TABLE 3.10 Irrigation of Agricultural Land—Summary: 1920-1969 [Data are for 17 Western States (Alaska and Hawaii excluded) and Louisiana, except as noted][a]

Item		1920	1930	1940	1950	1959	1969	1969[b]
Approximate land area	mil. acres	1190	1190	1191	1191	1189	1187	2263
Farms, total	1,000	1684	1820	1681	1430	1044	854	2730
Irrigated	1,000	222	264	290	289	267	210	257
Land in farms, total	mil. acres	488	553	611	699	715	733	1063
In irrigated farms	mil. acres	[c]	78	112	168	213	218	237
Land irrigated, total	mil. acres	[c]	14	18	25	31	35	39
Irrigation organizations:								
Number	1,000	[c]	4	6	10	9	8	8
Area irrigated	mil. acres	12	13	14	15	18	21	21
Investment from prior census year	mil. dol.	[c]	162	160	520	1040	1591	1607

[a] Source: U.S. Bureau of the Census, *U.S. Census of Agriculture: 1930, 1940, 1950, 1959,* and *1969, Irrigation of Agricultural Lands.*

[b] Data are for all states in the U.S.

[c] Comparable data not available.

TABLE 3.11 Federal Irrigation Projects: 1950–1971 (Acreage in thousands; value in $ millions)[a]

Year	Entire Area			Full Irrigation Service[b]			Supplemental and Temporary Irrigation Service[c]		
	Irrigable Acreage	Irrigated Acreage	Gross Crop Value	Irrigable Acreage	Irrigated Acreage	Gross Crop Value	Irrigable Acreage	Irrigated Acreage	Gross Crop Value
1950	6025	5077	578	3305	2716	311	2720	2361	267
1955	7368	6262	828	3826	3163	429	3542	3099	399
1960	8171	6900	1158	4326	3488	581	3845	3412	577
1965	9612	8012	1557	4540	3731	675	5072	4281	882
1968	9904	8387	1840	4683	3940	813	5221	4447	1027
1969	10140	8576	1885	4839	4070	867	5301	4506	1018
1970	10198	8570	1882	4844	4037	847	5354	4533	1035
1971	10560	8834	2124	4853	4050	943	5707	4784	1182

[a] Source: U.S. Bureau of Reclamation, *Federal Reclamation Projects, Water and Land Resource Accomplishments*, annual.

[b] Applies to irrigable land receiving its sole irrigation supply through Bureau of Reclamation-constructed facilities and to previously irrigated land in nonfederal projects where a substantial part of the facilities was constructed, rehabilitated, or replaced by the Bureau.

[c] Applies to irrigable land receiving irrigation water through Bureau projects in addition to supply from nonproject sources and to land for which water is delivered under temporary arrangements.

TABLE 3.12 Use of Land Resources, Selected Historical and Projected Years, 1959–2020 (in Thousands of Acres)

Land in Farms[a]	1959	1964	1980	1985	2000	2020
Cropland Harvested	311,285.2	286,708.1	292,242.6	285,585.4	271,920.4	255,656.1
Feed crops						
Grains[b]	125,395.0	93,658.2	102,936.3	99,795.9	91,147.2	63,016.8
Roughage[c]	76,432.0	78,829.4	68,787.2	67,446.5	64,396.1	61,862.7
Food crops						
Grains[d]	52,376.0	51,413.6	43,976.3	42,786.1	40,306.1	37,297.2
Vegetables, fruits, and sugar	8,992.9	9,638.1	9,024.3	9,006.4	9,154.7	9,078.6
Other[e]	3,176.0	2,923.1	3,105.9	3,087.8	2,982.9	2,908.1
Other crops						
Oil[f]	26,261.0	33,841.6	53,044.2	52,773.5	52,801.1	51,277.7
Cotton, tobacco, and miscellaneous	22,765.5	21,230.1	14,843.0	14,841.1	14,335.5	13,222.0
Total crops harvested[g]	315,598.4	291,533.7	295,717.4	289,737.4	275,123.6	258,663.2
Cropland not Harvested[h]	136,278.5	147,130.0	165,843.4	172,601.4	186,401.5	202,420.4
Total cropland	447,563.7	433,838.1	458,086.0	458,186.8	458,321.9	458,076.5
Forest and woodland	163,684.3	145,711.5	105,231.8	102,759.6	95,339.7	86,404.5
Pasture, range, and other land[i]	508,909.8	526,323.5	481,566.3	478,927.2	472,341.4	463,098.2
Total land in farms	1,120,157.8	1,105,873.1	1,044,884.1	1,839,873.6	1,025,003.0	1,007,579.2
Irrigated Cropland Harvested[j]	27,436.8	29,902.8	36,919.1	36,446.6	36,218.8	36,003.5
Feed crops						
Grains[b]	5,255.4	6,585.0	10,196.5	9,975.5	9,581.0	9,495.6
Roughage[c]	7,483.6	9,144.9	10,581.6	10,557.3	10,983.3	10,932.2
Food crops						
Grains[d]	2,961.9	3,785.5	4,208.9	4,086.9	3,869.2	3,772.2
Vegetables, fruits, and sugar	3,601.8	4,826.6	5,049.9	5,191.8	5,514.5	5,837.0
Other[e]	1,158.0	1,007.1	1,263.9	1,276.4	1,319.4	1,358.7
Other crops						
Oil[f]	395.0	479.8	1,264.1	1,292.4	1,380.3	1,443.5
Cotton, tobacco, and miscellaneous	3,465.0	4,281.2	4,743.6	4,454.6	3,961.8	3,565.8
Total irrigated crops harvested[k]	24,320.7	30,110.1	37,308.4	36,835.0	36,609.6	36,405.0

[a] Acreages are exclusive of Alaska and Hawaii.

[b–f] Footnotes *b–f* identify the 23 major crops for which acreages were projected; historical values for food, feed, and other crops include acreages of minor crops to account for total acreages of crops harvested.

[b] Includes corn, grain sorghum, oats, and barley.

[c] Includes hay and silage.

[d] Includes wheat, rye, and rice.

[e] Includes Irish and sweet potatoes, dry beans, and dry peas.

[f] Includes soybeans, peanuts, and flaxseed.

[g] Total crops harvested will not equal cropland harvested because of double cropping.

[h] Cropland used only for pasture or grazing, cover, crops, legumes and soil-improvement grasses, crop failure, cultivated summer fallow, and idle land.

[i] Land occupied by houses or other buildings, lanes, roads, ditches, land in ponds, and wasteland.

[j] Includes acreages for 17 western states, Arkansas, Mississippi, Louisiana, and Florida (1960 acreage reported under 1959 for Arkansas, Mississippi, and Florida).

[k] Total irrigated crops harvested will not equal cropland harvested because of double cropping and/or nonreporting.

Bonem in 1971.[31] Preliminary projections that are subject to revision have been made to 1985 and 2000 under the Water Resources Council's 1975 National Assessment Program (Table 3.14).

TABLE 3.13 Use of Land Resources, Selected Historical and Projected Years, 1959–2020 (in Thousands of Acres)

Land in Farms[a]	1959	1964	1980	1985	2000	2020
Cropland Harvested	311,285.2	286,708.1	307,624.4	317,000.6	354,270.2	356,423.3
Feed crops						
Grains[b]	125,395.0	93,658.2	96,127.4	98,778.5	113,774.4	111,738.7
Roughage[c]	76,432.0	78,829.4	73,664.9	74,524.6	77,485.6	81,086.4
Food crops						
Grains[d]	52,576.0	51,413.4	51,256.7	50,069.1	49,909.1	49,104.0
Vegetables, fruits, and sugar	8,992.9	9,638.1	9,471.7	9,634.4	9,892.5	10,274.1
Other[e]	3,176.0	2,923.1	2,922.7	2,869.0	2,708.3	2,678.8
Other crops						
Oil[f]	26,261.0	33,841.4	61,488.4	69,483.9	88,486.0	88,908.2
Cotton, tobacco, and miscellaneous	22,765.5	21,230.1	16,355.0	16,307.5	16,319.9	16,934.9
Total crops harvested[g]	315,598.4	291,533.7	311,286.7	321,665.9	358,575.7	360,725.1
Cropland not Harvested[h]	136,278.5	147,130.0	150,510.3	141,166.2	104,051.8	101,653.2
Total cropland	447.563.7	433,838.1	458,134.8	458,186.8	458,321.9	458,076.5
Forest and woodland	163,684.3	145,711.5	105,231.8	102,759.6	95,339.7	86,404.5
Pasture, range, and other land[i]	508,909.8	526,323.5	481,566.3	478,927.2	471,341.4	463,098.2
Total land in farms	1,120,157.8	1,105,873.1	1,044,932.9	1,039,873.6	1,025,003.0	1,007,579.2
Irrigated Cropland Harvested[j]	27,436.8	29,902.8	37,463.6	36,935.8	37,042.6	37,184.3
Feed crops						
Grains[b]	5,255.4	6,585.0	10,079.8	9,799.3	9,567.3	9,516.2
Roughage[c]	7,483.6	9,144.9	10,648.8	10,681.3	11,221.8	11,072.5
Food crops						
Grains[d]	2,961.9	3,785.5	4,563.8	4,488.3	4,541.9	4,490.6
Vegetables, fruits, and sugar	3,601.8	4,826.6	5,396.4	5,514.8	5,866.5	6,463.8
Other[e]	1,158.0	1,007.1	1,265.0	1,278.2	1,289.5	1,328.6
Other crops						
Oil[f]	395.0	479.8	1,113.5	1,090.4	1,054.1	1,090.3
Cotton, tobacco, and miscellaneous	3,465.0	4,281.2	4,789.1	4,471.9	3,892.5	3,623.8
Total irrigated crops harvested[k]	24,320.7	30,110.1	37,856.3	37,324.2	37,433.4	37,585.7

[a] Acreages are exclusive of Alaska and Hawaii.

[b–f] Footnotes *b–f* identify the 23 major crops for which acreages were projected; historical values for food, feed, and other crops include acreages of minor crops to account for total acreages of crops harvested.

[b] Includes corn, grain sorghum, oats, and barley.

[c] Includes hay and silage.

[d] Includes wheat, rye, and rice.

[e] Includes Irish and sweet potatoes, dry beans, and dry peas.

[f] Includes soybeans, peanuts, and flaxseed.

[g] Total crops harvested will not equal cropland harvested because of double cropping.

[h] Cropland used only for pasture or grazing, cover, crops, legumes and soil-improvement grasses, crop failure, cultivated summer fallow, and idle land.

[i] Land occupied by houses or other buildings, lanes, roads, ditches, land in ponds, and wasteland.

[j] Includes acreages for 17 western states, Arkansas, Mississippi, Louisiana, and Florida (1960 acreage reported under 1959 for Arkansas, Mississippi, and Florida).

[k] Total irrigated crops harvested will not equal cropland harvested because of double cropping and/or nonreporting.

To test the usefulness of a simplistic national "projection model," based on an extrapolation of past production growth trends and fixed water requirements per unit of output, the Series E OBERS growth rates were used with 1970 agricultural and steam–electric withdrawals data and the 1973 Census of mineral industry and manufacturing water-use data. Essentially the gross outputs of a 400-sector 1972 national interindustry table, updated from 1967, were aggregated to conform to the OBERS industry classification scheme. The OBERS growth rates of earnings that had been projected by sector to 2000 and 2020 in constant dollars were calculated in index terms and then applied to the 1972 gross domestic outputs by sector to project these to the target years. Water-use coefficients for the base year were calculated for the industry classifications in the form of water use in billions of gallons per day per million dollars of product output. These coefficients were then multiplied into the projected levels of constant-dollar output to yield the estimated values of water use by sector. These values have been plotted along with the other projections in Figures 3.4 – 3.11. The results of the simplistic projection model compare favorably with some of the middle-range projections developed by Wollman and Bonem. The values of the water coefficients used in the simplistic model for the mineral industry category may be low because of the fact that the Census data, as presented, cover only 7 percent of the total number of establishments. The 7 percent that are covered are nevertheless stated to represent some 98 percent of total water withdrawals.

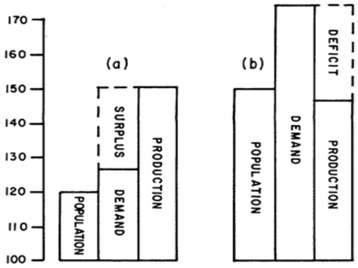

FIGURE 3.3 Projections to 1985 of population, food demand, food projection, and food valance in (a) the developed countries (including eastern Europe and the Soviet Union) and (b) the developing market economy countries. 1969–1971 = 100. Data source: Reference 68.

If the climatic changes that portend are in fact realized, then the irrigation demands may be substantially greater than the preliminary Water Resources Council second national assessment estimates as they are currently shown. If increased irrigation demands are to be met both in the traditionally semiarid areas of the West and in the dry farming areas of the Midwest and East, then something approximating a fixed water input per unit of output may ultimately be a more realistic assumption to be made.

The agricultural sector in the United States is basic to the support of the large concentrations of population in metropolitan and suburban areas. However, this sector is extremely vulnerable to any adverse climatic change that could lead to a series of crop failures. Additionally, household water needs are similarly vulnerable in many localities because of limited reservoir capacities. The combined conditions of drought in agricultural areas and insufficient capacity in public water supplies for metropolitan areas could lead to unstable political and economic conditions where populations are highly concentrated. Unforeseen shortages of water for any protracted period of time may be difficult to contend with in terms of public health and safety. While results of the simplistic projection model of water demands constructed by the authors for the years 2000 and 2020 based on current water-use data and economic growth rates associated with a series E population growth compare favorably with the middle-range projections developed by Wollman and Bonem, both sets of forecasts, as well as others such as

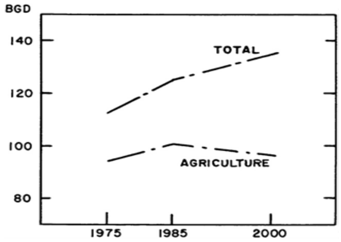

FIGURE 3.4 1975 Water Resources Council projections for consumptive water use. Key: _ _ _, constant-water-use coefficient model; __ _ __ _; Water Resources Council preliminary projection, 1975; _ _ _ _ ,Water Resources Council, 1965; __, Wollman and Bonem[31] (high, medium, low projections). BGD, billion gallons/day.

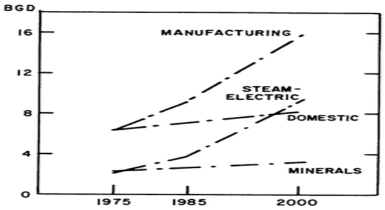

FIGURE 3.5 1975 Water Resources Council projections for consumptive water use. Key: See Figure 3.4.

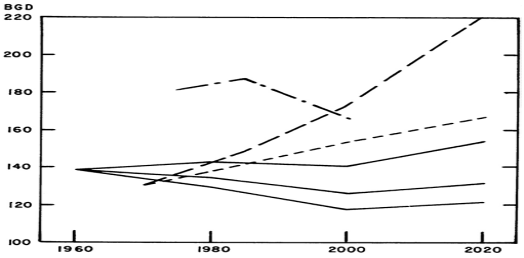

FIGURE 3.6 Agricultural water withdrawals. Key: See Figure 3.4.

TABLE 3.14 Annual Water Requirements

Water Requirement Categories	Withdrawal Use		(mgd) 2000	Consumptive Use		(mgd) 2000
	1975	1985		1975	1985	
Domestic Central	21,520.4	24,698.0	29,086.0	5,003.4	5,744.8	6,756.0
Domestic Noncentral	2,072.7	2,296.0	2,371.7	1,288.5	1,392.1	1,417.5
Manufacturing Total	58,176.8	33,086.5	45,701.6	6,275.0	9,199.9	15,758.3
Food and kindred	2,500.6	1,440.3	1,137.6	310.3	465.7	770.5
Paper, pulp, and board	8,595.6	5,821.5	5,193.2	1,039.7	2,065.0	4,112.6
All other manufacturing	4,910.7	2,496.5	2,606.7	598.6	865.0	1,400.6
Textile mills	559.6	265.7	211.6	65.1	93,1	144.5
Chemicals	14,005.4	5,867.6	5,445.4	1,305.5	2,128.3	4,260.1
Primary metals	17,324.0	5,591.0	3,398.0	2,007.0	2,282.0	2,685.0
Transport, machinery	1,331.4	579.4	479.4	143.8	226.7	364.4
Petroleum refining	2,313.8	1,578.4	1,201.6	533.5	687.5	955.4
Minerals, Total	7,506.1	8,810.4	10,912.4	2,333.2	2,628.4	3,145.8
Metals	1,081.2	1,288.2	1,605.3	233.5	272.5	300.1
Nonmetals	3,518.7	4,385.7	5,745.6	470.8	599.1	785.0
Fuels	2,907.4	3,137.0	3,622.4	1,627.9	1,758.9	2,022.4
Crop Irrigation	179,053.4	184,984.5	163,652.9	92,024.5	98,153.5	93,742.2
Livestock	1,851.9	2,153.1	2,444.1	1,851.9	2,153.1	2,444.1
Steam Electric	92,602.0	86,801.0	70,047.0	2,103.0	3,647.0	9,147.0
National Parks	13.8	18.0	21.7	10.3	13.5	15.9
Fish Hatcheries	628.0	697.2	726.3	0.0	0.0	0.0
BLM Lands	1,050.7	1,129.9	1,232.8	1,050.7	1,129.9	1,232.8
National Forests	393.0	591.5	793.4	393.0	591.5	793.4
Total Requirements	364,868.8	345,266.6	326,990.0	112,333.5	124,653.5	134,453.1
Man-made Evaporation	13,114.0	13,556.2	13,779.8	13,114.0	13,556.2	13,779.8
Total Requirements plus Evaporation	377,982.7	358.822.8	340,769.8	125,447.5	138,209.7	148,232.9
Net Exports	450.7	651.7	862.2	450.7	651.7	862.2
Net Depletions	378,433.4	359,474.5	341,631.9	125,898.2	138,861.4	149,095.1
Groundwater Withdrawals	68,665.5	66,410.5	63,481.5			
Net Imports	0.0	0.0	0.0			

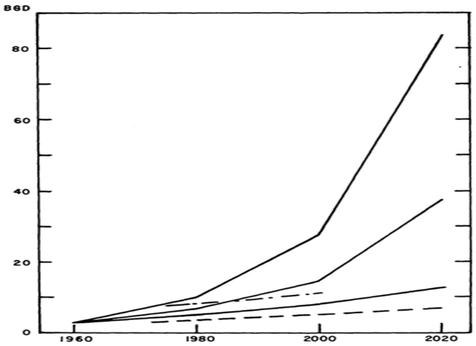

FIGURE 3.7 Mining water withdrawals. Key: See Figure 3.4.

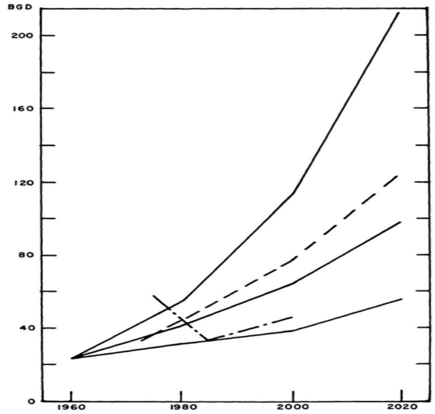

FIGURE 3.8 Manufacturing water withdrawals. Key: See Figure 3.4.

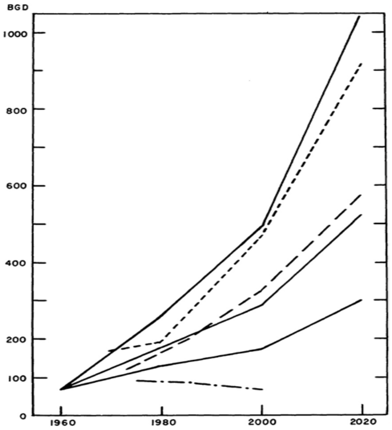

FIGURE 3.9 Steam-electric water withdrawals. Key: See Figure 3.4.

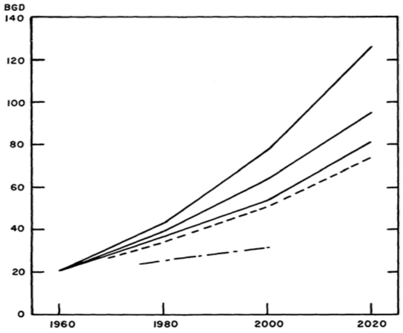

FIGURE 3.10 Municipal water withdrawals. Water Resources Council data are for *domestic use only.* Key: See Figure 3.4.

those developed by the United States Water Resources Council for 1968 and 1975, may substantially understate agricultural water demands if any unfavorable climatic change is experienced during the coming 50-year planning period.

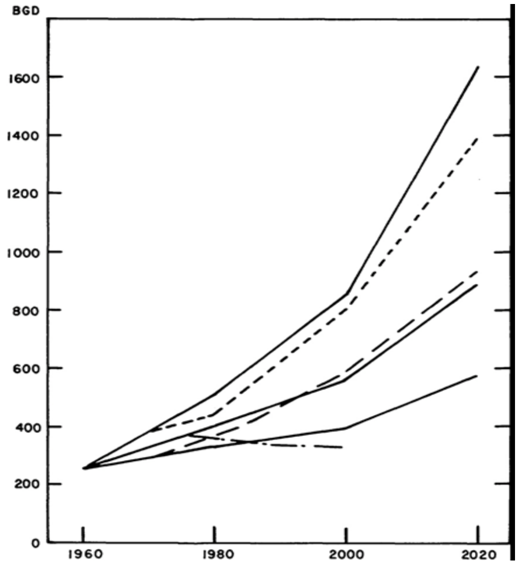

FIGURE 3.11 Total water withdrawals. Key: See Figure 3.4.

The authors are indebted to Nathaniel Wollman and Warren Hall for helpful review comments given for an earlier draft of this chapter.

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Climatic Change and Water Law

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INTRODUCTION

Water law could be defined as the formal statement of man's reaction to the aqueous element of his environment. This rather unusual definition would be especially appropriate for present purposes because the view from this angle brings out a not always obvious constraint: man must shape his law to the environment *as he perceives it.* If his picture of the physical universe is false, he is not likely to get good results from a law based on the misconception. A century ago, when judges thought that groundwaters were “vagrant, meandering drops” moving in “unknown and unknowable courses,” according to “secret, changeable and uncontrollable forces,” they developed rules of law that would not be suitable for a modern hydrogeologist trying to manage withdrawals from a large groundwater basin with the help of a data bank and a computer model. But, of course, the modern administrator does not use the century-old law based on ignorance. The legislature has replaced it with a set of flexible controls that enable him to manage the water in accordance with the latest available scientific information. The law, like other human institutions, has grown and changed in response to increases in man's knowledge. While one function of law is to give stability to institutions and predictability to the results of action, often the strength of the law will lie not in immutability but in capacity for change and flexibility in the face of new forces.

This proposition has special significance for this paper. Today's water laws are based on certain implicit assumptions about climate and water occurrence derived from observations of actual events. Our plans for water uses and projects are made in the light of predictions based on these observations. Yet the scientists on this panel now question those assumptions and predictions. Climate has changed in the past, and the climate we enjoy today could be replaced with a quite different one tomorrow. We plan our developments on notions of “normal” precipitation and “predictable” drought, but the data are sketchy, and statistical theory seems to indicate that our premises are shaky. We could come up against a drought that lasts longer or is more intense than any we have known; we could find that it is a “permanent” drought, a climatic change that represents a new normal and promises to persist indefinitely.* Legal questions inevitably arise: how will our water law work under such unforeseen conditions, and will we need to change it? One answer seems obvious. If the past can be shown to be an uncertain guide to the future, we would be wise to plan for the unpredictable. Law is, of course, a planning tool in itself (it encourages actions most of us deem desirable and discourages those deemed harmful), and the most valuable consequence of a new realization of uncertainty might be that we would build into the law mechanisms for change and give our rights and institutions a flexibility designed to minimize dislocations when change in climate occurs.

We face one quite predictable change wholly unrelated to climate. With population growth, increased industrialization, and greater affluence, more water is going to be needed in the future than is used at present. This will create a “water shortage” just as much as would a drought, because shortage is a function of both supply and demand. An increased demand for a stable supply will produce much the same pressures as will a decreased supply. Since the unpredictable changes that are of present concern will produce (or aggravate) the same result as the predictable change, we may find hints on how to handle the unpredictable in the way in which we attack the predictable.

When the demand for anything exceeds the supply, we have a common type of problem. Something has to give. We can attack the problem from either end. We can cure a water shortage by increasing the supply (at the time and place of demand) by building a dam and storing water during good times so it will be present during bad times, by importing water from some distant place where the supply exceeds the local demand, or by seeking a new source such as groundwater. Or we can reduce the demand by restricting the number of claimants (for instance, to riparian landowners), by prohibiting certain uses, by limiting quantities used, by increasing the price of water beyond the ability of some users to pay, or by buying out some existing user. For purposes of this paper, we will call the first type of adjustment the “engineering solution,” the second an “economic solution,” although obviously the choice to build or buy depends upon economic considerations.

This process is what law is all about. Water law is a part of resources law, a part of all law, and while it may be complex, it is not necessarily mysterious. The object of all law was stated by Dean Roscoe Pound of the Harvard Law School[1]:

What we are seeking to do and must do in a civilized society is to adjust relations and order conduct in a world in which the goods of existence, the scope of free activity and the objects on which to exert free activity are limited, and the demands on those goods and those objects are infinite. To order the activities of men in their endeavor to satisfy their demands so as to enable satisfaction of the whole scheme of demands with the least friction and waste has . . . been what lawmakers and tribunals and jurists have been striving for.

This of course is the economist's principle of efficiency, Jeremy Bentham's golden mean of the greatest good for the greatest number, and the general desire of all men to derive the maximum benefit and satisfaction from their activities and their environment. The water laws that we hope will help us to reach these goals take many forms. Much water law deals with “water rights,” the identification and regulation of claims to private use. Much of it is institutional—the powers and forms of governments, agencies, and organizations that control and develop water resources. Much of what we now call environmental law is a part of water law or is applicable to water-related activities.

Water rights offer the easiest place to start. These are property rights, and their existence and specificity are a reflection of their place in the economic evolutionary scale. If a resource is so plentiful that it is not affected by man's actions toward it, we regard it as a “free good,” a common pool in which all may participate. When claims upon it increase to the point that one person's use harms the other's or threatens the existence of the pool, or when shares in the pool become too small to be useful to anyone, man needs and enacts in one form or another laws that restrict the number of participants or that control or regulate their activity or that abandon commonality and carve up the resource into individual, identifiable, enforceable, and transferable property units.

WATER RIGHTS

The orthodox classification of American water law starts with a division into the eastern doctrine of riparian rights and the western law of prior appropriation. We will take up the latter first, since appropriative rights were designed for a water-short area where there is not enough for all and are therefore much more structured and precise than the riparian rights of the eastern humid areas, where the assumption has been that there is plenty of water, at least for the owners of the stream banks who can claim rights to their use.

PRIOR APPROPRIATION

The law of prior appropriation had crude beginnings in the California gold rush. Thousands of forty-niners crowded the diggings at the mouths of the Sierra canyons and staked “placer claims” on the alluvial benches and fans. They staked similar claims to the water needed to wash the gold from the gravel. Since there was neither

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*Most water law deals with allocation and management of a scarce resource. Although unpredictability could mean more water than expected and climate could change for the better, changes in this direction would create few legal problems worth discussing.

gold nor water enough for everyone, both were put on a "first come, first served" basis. Claim jumping was discouraged by Colt and Winchester. When the Great American Desert was found to be habitable, the first settler in a valley took first choice of the land and enough water to irrigate it, the second comer had to make do out of what was left. These self-made laws were recognized by courts and formalized by legislatures, and today prior appropriation is a quite civilized system of state grants of property rights, enforced and regulated by administrative agencies with substantial offices, rooms full of records, and squads of men in the field.

One of the most important features of modern appropriation law is the permit system. Any person desiring to start a new water use must get a permit from the state. The permit may be denied if there is no unappropriated water in the source and if the new right, if granted, would conflict with existing rights. The permit may also be denied if the proposed use would not be "in the public interest." Using this power, water officials have chosen the better of two competing projects: they have denied permits for projects that do not comport with state water plans, and they have placed conditions and limits on permits in order to prevent serious environmental harm.

An appropriation is a definite and identifiable piece of property. Its boundaries are marked by the quantity that may be diverted from the source, the place the diversion may be made, the use that may be made, and the date that tells when the right may be used. The quantity of water is expressed in terms of cubic feet per second, the rate at which water may be diverted from the source,[2] unless the appropriation is one for storage, in which case the water allowed is expressed in total quantity in acre-feet.[3] An appropriation need not be used on riparian land or even in the valley where the water originates.[4] Most are for irrigation, but every type of beneficial use of water may have an appropriation to serve it: municipal use, manufacturing, production of hydroelectric or steam power, mining, ore processing, recreation—beneficial use is not a closed category.[5] This property can be sold, the use may be changed, or the place of use may be changed, provided that proper formalities are observed and approval is obtained.[6]

The rule of priority operates even in a normal year, not only in time of shortage. On an unregulated stream (one without storage dams) from which many irrigators draw water, all may open their ditches in the spring as the mountain snowpacks melt and the stream is high. As the flow decreases during the dry summer, the diversion works are shut off in inverse order of priority. The last ditch is first closed; the first need never be. The entire burden of the lessened flow falls on the junior appropriator. He loses all his water; the senior, none. Some have called this a harsh rule, but it should be remembered that the low flow is insufficient for all, and that equal shares for everybody would be sufficient for none. The rule of priority does guarantee a firm supply to all for whom the source is sufficient, and the senior irrigators can build a stable agriculture unmatched in humid climes. The junior appropriator is not unlike the farmer in a semihumid area who must take his chances on rain. If he can only count on spring flood water, he will grow one crop of wild hay and will not plant a late maturing crop like sugar beets. The senior may grow an orchard or a vineyard, the junior will plant corn, since he may gamble on the loss of an annual crop but not of a permanent investment.

Since the low flow will accommodate so few users, storage is desirable to detain the spring flood for release in the late summer. The rule of priority also determines who will pay for the dam—it is the junior appropriator who will get the benefit from it. In return for his investment, he will often have a better right than many seniors, since his stored water will carry him late into the year when the base flow becomes insufficient for all but a few. For this reason, seniors will often join in a dam project in order to receive supplemental water to firm up their late season supply.

Actually, there is a good deal of sharing among western water users. On many streams the latest projects are often the largest. The early small diversions were made with individual effort or small group investments, and when storage became a necessity, economies of scale called for large dams and long canals, which required government capital, often government subsidy. The large project usually has a single priority for all who receive its water, so if there is a short supply, all will share equally, although operating plans or contractual arrangements may provide that municipal or industrial water receives a priority over irrigation, and irrigation over power. A noteworthy feature of prior appropriation is that if storage can be provided not only to save the spring floods for use later that year but also to save the surplus from good years for use in the bad years, the physical effect of priority disappears. There are no junior appropriates, and everyone has a firm right to a firm supply—a state of equilibrium reached on many western rivers where the Bureau of Reclamation has built sufficient dams.

As demands increase and new demands arise, they are accommodated within the system. If there is unappropriated water available during the period it is needed, the new user is for all practical purposes a senior appropriator. If the supply may or may not be available but the risk seems worth the candle, he simply becomes another junior. If a year-round supply is needed, as for a factory or industrial plant, storage may be provided. But when all the supply is in use, when all the dam sites are used, or the costs of dams become too high, a new user must purchase the water right of a senior appropriator or of a junior with storage. He can do this, or course, if his new use will have a higher productive value than the existing use. In practice, this means that cities and industrial users, which can afford to pay more for water than can most farmers, buy out the water rights of agricultural users.

Applying the rule of priority to the physical results of drought or climatic change may have some unexpected effects. It is not correct to think that drought will simply fall upon the most junior appropriators and wipe them out. In the long run, of course, the juniors will be those squeezed out, but many holders of senior and intermediate priorities may be affected. It will depend in part on the nature of the change, whether it takes the form of an extraordinarily "subnormal" water year, an "unexpectedly long" series of low water years, or a "permanent" change in climate that reduces the long-term yield to some new norm. In most subnormal years, the high water begins to drop at an earlier date than usual, and as the flow subsides each junior appropriator will "go out of priority" and must close his intake some indeterminate number of days earlier than he would have if the year had been within the "normal" range. On an unregulated stream, the odds will be changed on all the bets. The original marginal junior rights become untenable and forfeit, the moderately secure rights are now risky, and the relatively certain are smaller in number. If the subnormality consists of unusually low base flows, the seniors who depend on late summer flows may get hurt the worst. If the drought flattens out the peaks and there is less high water than expected, then junior storage projects bear the brunt. Where large-scale storage has been built to equate the supply, the planners had in mind some combination of bad years to be hurdled. If that "design drought" were never exceeded, every right would be as good as any other; but if the dams are finally run dry, a substantial block of shares—all of those that depend on the junior project—will fail together.

Variations in the pattern of multiyear drought will also change the incidence of hardship. The North Platte River, to take an example, is a fully regulated stream on which the annual and perennial fluctuations have been ironed out by two large projects with different priorities. The earliest, Pathfinder Dam, has low storage in proportion to the land it serves, while the more recent project, Seminoe Dam, has large storage but a late priority. A short-term drought with several years of very low flows would dry up Pathfinder but might be well within the carryover capacity of Seminoe, while a long sequence of mediocre years would hardly affect Pathfinder but would ruin the Seminoe project.[7]

The law of prior appropriation already has some provisions for flexibility that will enable the water users to cope with these rather assorted effects of long-term drought or climate change. Some make economic solutions possible. Even if self-interest does not keep fools from rushing in, the permit system enables state water officials to deny applications for permits if there is no unappropriated water available and thus limit the number of claims or prevent more from arising. To the extent that the junior appropriations serve marginal enterprises such as farms producing low-value crops, the simple operation of priority will result in the cessation of those water uses that society can best afford to lose. But there is nothing in the priority system that prevents early uses from being the less valuable or that ensures that the last are the least valuable. An intermediate right now made more risky may support an investment for which the new magnitude of risk may be intolerable. And, of course, it is quite possible that in a water-scarce area all water is put to quite valuable uses.

In these cases, the transferability of the appropriative right will provide the adjustment mechanism. Juniors with valuable uses will purchase senior rights. The holder of a shaky right may buy a storage right. The participant in a project whose reduced share is insufficient for his needs may buy another share to add to it. It must be noted, however, that there are some restrictions on these processes. Some states place limits on transfers, all subject them to the rule that the transfer and the new operations under the changed water right must not injure other appropriators, and all must be approved by state water officials in what often turn out to be costly and long drawn-out proceedings.

If the values that could be destroyed by drought are high enough to justify the costs of new works, and if those works are less expensive than the economic solutions, then prior appropriation will also be found quite well suited to engineering solutions to drought. The problems occur when there is not enough water in a particular place at a specific time, and moving water about in time and space is the normal job of prior appropriation. If excess storage capacity were desired as a preventive measure so that when the water was needed it would be available, the law allows high flows to be transformed into carryover storage, although the water officials may have to be convinced that the holdover is reasonable and the danger real.[8] If new storage is needed as a rescue measure, the law's normal procedures are available. If a transdivide diversion is needed to bring water from a water-rich to a water-short area, in most states there are no restrictions on the necessary interbasin transportation.

EASTERN WATER RIGHTS

Riparian rights used to be the principal basis of water use in the eastern states, but this is no longer true. Today, riparian uses are overshadowed by the large abstractions of cities and other public suppliers with quite different rights, and the common law is overlaid or superseded by many regulatory statutes. It still has its importance, although often only as the background against which the new laws operate.

The typical statement of the basic riparian law is that every landowner has a right to make a reasonable use of a stream or lake that flows through or borders on his land but that this right is qualified by the equal rights of other riparians to make a similar use.[9] This vague generality is frequently stated by the judges but really tells us very little. When analyzed, riparian law turns out to be not so much a system of allocation of property rights as it is a combination of a laissez-faire rule that lets most riparians do pretty much as they please with the abundant water at hand and a "fire-fighting device" that gives a legal mech anism for settling the few disputes that do arise. It is very difficult to define the boundaries or limits of a riparian right with certainty or to state the specific action it permits, as we did with an appropriation. For this reason, most riparian law is framed not as property rules but as tort law—rules that define a wrong and tell us not what the owner of the right can do but what others may not do to him.[10] The first requirement of a violation of riparian rights is that the plaintiff must prove that the alleged violator has inflicted substantial harm upon the plaintiff's reasonable use.[11] There is an old legal maxim, “the law does not concern itself with trifles,” and suits to enforce a naked right to the natural flow of the stream are no longer favored. The minimum flow of a stream or the natural level of a lake will be protected, however, if a defendant destroys the values added to rural land by “living water” or the site values of lakeside properties.[12] Second, the “equal rights” feature means that the law will try to accommodate as many rights as possible. One person's use will not be stopped as a violation of another's right even though it causes harm, if the harm can be avoided by some adjustment of the works or operations of one party or the other so that both uses can co-exist. In many of the riparian rights cases, the question of “reasonable use” really breaks down to the tough question of which party should reasonably be required to pay for the improvement—the person whose use must be improved or the person who gets the benefit of the improvement.[13]

A corollary of the principles of equality and coexistence is the riparian rule of sharing. Since all users have equal rights, they must share the hardship when there is not enough for all, and each must make a proportionate reduction in his use.[14] But when coexistence of incompatible uses is impossible, when a reduced quantity would make an existing use inoperable or unprofitable, or when a new use takes the water supply from an existing reasonable use, the courts have almost universally protected the existing user from encroachment by the innovator. Some of the earlier cases said that the rule of equality foreclosed consideration of priority when determining the reasonableness of an interfering use and that the interests of the two parties would have to be balanced.[15] But when a new use will destroy the values of land, investments, and enterprises based on a use of water, the new use seems quite unreasonable, and priority seems to loom large in the balance. No matter what the courts say, their decisions quite uniformly protect the prior user and enjoin the destructive newcomer or make him pay for the harm he causes. This may often be a subliminal recognition of what the economists call the “Pareto compensation principle,” or an unexpressed feeling that equity and justice, “reasonableness” if you will, require the gainer to pay the loser. At any rate, the courts have protected irrigators from manufacturers,[16] manufacturers from irrigators,[17] fishermen from both[18] —depending on who was there first and whether the latecomer is enriching himself at the expense of the prior user. Even when all uses are for the same purpose, such as recreational enjoyment of a lake, the courts have favored the early bird, and when newcomers start to overcrowd the facilities, the judges put limits on use that prevent destruction of the aesthetic qualities of the water.[19]

Riparian law theoretically limits rights to water to riparian proprietors, but while “nonriparians” may have no rights to water they certainly make many uses of water. There are thousands and thousands of householders, farmers, dairymen, manufacturers, mine owners, food processors, and subdivision developers who have somehow acquired access across neighboring land to the streams and who pipe water from it. Since they cause no serious harm, they are not sued. They have no rights, no ground of complaint if a riparian causes harm to them by destroying their supply,[20] but since water is abundant, many of them do not seem to fear such action. Some of them may have acquired a “prescriptive right” by long continued use and are now safe; others may have tried to buy rights to the stream as well as access to it. The success of this attempt may depend on the state in which the action took place. The courts of some states have permitted the sale of a riparian right to a nonriparian and allowed him to do with the water whatever the original riparian could have done.[21] Other courts have said that a riparian right cannot be transferred so as to be effective against third parties.[22] This means that the nonriparian is safe from suit only from the person he made his deal with, and he is totally safe only if he can buy his peace from every downstream riparian who might complain of his use and from every upstream riparian whose future use might harm him. This is a clumsy and expensive process, but it has been done.

There seem to be no cases in which one riparian has tried to buy out another and claim a double share against the rest. On principle, however, the same considerations ought to apply. If a riparian right is transferable, it should be transferable to a riparian as well as to a nonriparian. Even if it is not, there is nothing to prevent a group of riparians from settling their differences by contract and agreeing between themselves what is each one's reasonable share or reasonable use of the water.[23]

The major diversions from eastern streams are now those of municipalities, public utilities, metropolitan water works, and rural water districts, not those of the little grist mills and woolen mills that competed with farmers during the formative period of riparian rights. Municipal water rights arise not from riparian law but by virtue of the superior position given to these agencies by legislatively granted powers to take waters by eminent domain. The city or its public supplier may condemn the rights of or negotiate arrangements with principal riparians in advance, but often it merely builds its works, takes the water, and sits back to see who sues it. In such “inverse condemnation” suits, compensation or damages are paid to any riparian who can prove injury to his right or use.[24] Very often nothing is paid because no serious damage has been done. The city does not literally take over and exercise the water right formerly held by the landowner, as it would with an appropriation; the riparian right still exists, subordinated to the city's right.

In 10 of the 31 eastern states, the common law of riparian rights has been superseded or substantially modified by the enactment of a statutory water code.[25] Under all of these, a permit is required for all substantial and important uses of water, at least in problem areas. This gives state control at a very important point and could be used to prevent future conflict by denying permits to undesirable uses, to avoid disputes by inserting conditions in the permits that prevent the harm, or to resolve them in advance by specifying priorities. Not much of this has been done. Several of the statutes inject some priority in the picture by providing that in issuing the permits the authorities must protect vested rights and existing users. But with three exceptions the eastern permit statutes are limited to control of new uses and do not deal with the problem of drought or shortage. Most of the statutes are silent on the point of whether the permit rights are transferable, and several laws specifically state that they are not. Flexibility of water use is provided by issuing short-term permits that will allow the state water officials to reallocate the water to new and better uses when the existing permits expire.[26]

This is an impressionistic picture of eastern water law, slapped on with a broad brush. Although it lacks precision and definiteness, it at least shows that under any system of eastern water law the cities are going to come out on top if unprecedented drought should occur or if the generous eastern streams should dwindle permanently. In a riparian state, the cities' rights, usually to a specific quantity fixed by the capacity of the works, would be served in full and the riparians would bear the full brunt of the shortage. They could suffer greater damages than before or new harms, but they would have no right to reopen the compensation suits or make new claims if the time allowed by statute to file such suits had expired. In the permit states, the administrators who readjust water rights are likely to prefer the cities over the irrigators who deplete the streams or the downstream power companies who claim the full flow.

What if cities find that they are themselves in competition for the same supply? A few such cases have already occurred, but each has been decided on a different basis, and no one can predict a general rule. A Massachusetts case was decided on priority; the city with the first claim had the better right.[27] Two cities in upstate New York relied on authorizations from a state agency, and the agency was held to have the power to modify its grants and reallocate the water by administrative fiat.[28] In the third case, two cities across a state line from each other on a small interstate stream were forced to share on the basis of riparian principles of reasonableness.[29]

If drought strikes well-used eastern streams subject to many riparian claims, we may expect many more lawsuits that require adjustments between existing users, enforce the rule of sharing between them, put a stop to nonriparian uses, or impose restrictions on new riparian enterprises. When a reduced supply is unsuitable for an enterprise such as a steel mill or power plant, when a riparian has a need for a specific and steady rate of flow, or when a new user needs water for a highly valued purpose, there will undoubtedly be attempts at economic reallocation and transfer of existing shares, despite the difficulties of negotiations.

The law of riparian rights is not very conducive to engineering solutions undertaken by the private sector. Storage of large quantities for long periods has been held an unreasonable use.[30] Riparian rights must be exercised within the watershed of the stream,[31] so transdivide diversions become nonriparian uses, fair game for any future riparian use. Storage and importation of water may still be undertaken by cities and other public agencies, of course, and the principal municipal problem induced by a change in water occurrence will be that costs of buying out riparian rights will be magnified as those rights increase in value with the decrease in supply.

In the permit states, the courts will have to fill in the blanks in the statutes that regulate the initiation of uses but that give no rules for distribution when there is not enough water for all. Priority, sharing, or administrative distribution are the possible choices. Only three of the statutes indicate which is to be followed. Mississippi has a simon-pure prior appropriation law on the western model.[32] The Florida law gives an elaborate machinery for planning the distribution of water during shortages by reducing withdrawals, restricting some uses, suspending permits, and if things get bad enough to be called an emergency, the plans are scrapped and an official steps in to apportion, rotate, limit, or prohibit water uses.[33] The Kentucky statute empowers state authorities to handle a drought or emergency by balancing the water rights and available water between uses and temporarily allocate it and restrict withdrawals to serve “the best interests of the public.”[34] These laws were enacted in times of plenty when it seemed easiest for the legislators simply to put all water in the hands of a wise administrator with directions to distribute it so that it would do the most good and best serve the public interests. We may find, however, that that wise administrator takes on some aspects of a dirty bureaucrat when he decides, as he must, that the Smith family's potato farm must dry up while the Joneses' vegetable gardens continue to prosper or that both families must lose their investment and be deprived of their livelihoods so that their water may be given free to residents and commercial establishments in the city, and that the Apex Plastic Company may continue to pay dividends, while the Acme Canning Company goes bankrupt.

GROUNDWATER

More than a century ago an English court was faced with a dispute between a mine owner who was de-watering his mine and a nearby tanner whose spring dried up. Since the court did not know what was happening underground and could not figure out what rules should regulate groundwater, it ducked the issue by giving the overlying landowner complete freedom to act without liability.[35] It did this by declaring that the water, like the rocks and minerals, belonged to the owner of the surface of the land, who might do as he pleased with his "property" (in this case, throw it away). Some American courts still follow this "English rule of absolute ownership." It should be noted that this ownership of water is not so absolute as it sounds, since a neighbor with a deeper well and a more powerful pump can suck it out from under another's land and make it *his* property. The rule gave landowners the go-ahead to develop, and since harms were rare and usually small, the rule worked fairly well. But the invention of the high-capacity pump increased the capacity to inflict serious harm, and about the turn of the century many cities turned to groundwater for supplemental and unpolluted supplies. Their large withdrawals from small country plots left the old oaken bucket hanging high and dry in many neighboring farmyards. In a series of cases, all entitled *"Smith* v. *City of Jonesville*" or the like, many courts applied the "American rule of reasonable use."[36] This is not so reasonable as it sounds, since the rule permits the use of the water on overlying land without regard to damage but holds it unreasonable to "transport water to distant places for sale"—that is, use it for domestic and commercial purposes in cities. What it means, of course, is that the city must pay the farmer for deepening his well or bringing water from another source.

It can be seen that neither of these rules of liability or nonliability creates water rights in the sense of allocating water. In nearly all of the cases it can be determined or inferred that there was enough water for both parties and the real dispute was over the facilities—who should pay for a deeper well for the first user or his increased pumping costs. The first real attempt at apportioning the supply came in the western states when irrigators began to withdraw very large quantities. The California courts evolved the reasonable-use rule into the "correlative rights doctrine": the user on overlying land has a better right than a person who takes the water to distant places, and as between themselves, the overlying owners have correlative rights, equal and proportionate shares.[37] Most of the western states, however, following the lead of New Mexico, apply the law of prior appropriation to groundwater and have a single water law and set of procedures for both groundwater and surface water or have separate surface and groundwater codes that implement the basic priority doctrine with somewhat different procedures.[38]

When man places different types of elements on groundwaters with different physical characteristics, not all of these doctrines will reach the most desirable result. One problem has arisen when water tables drop (or artesian pressure falls) as more and more wells are drilled, but total withdrawals remain within the recharge. The English rule and the correlative rights rule would probably require all parties to bear their own costs as they follow the water deeper. As between agricultural uses, this equal treatment probably works well. Many appropriation laws have express statutory provisions to the same effect—that priority does not mean that earlier users may require water levels and pressures to remain the same. Very often the parties are not on an equal footing, however, because municipal and manufacturing users can pay more for water (and pumping costs) than can an irrigator. Under the American rule, and under some appropriation laws, the farmer cannot be driven beyond his economic reach, and some cities and industrialists would have to bear these expenses they impose on their rural neighbors.[39]

If withdrawals reach the "safe yield," the limit of recharge, yet it is clearly desirable to maintain the source as an annually renewable flow, neither the English rule nor the American rule has any mechanism for limiting development by stopping the drilling of new wells. The California rule would operate to restrict overdevelopment by preventing the outsiders from drilling, but each overlying landowner could have a well. Under prior appropriation law, overdevelopment could be stopped by simply denying applications for new permits.

If the safe yield has been exceeded and it is desirable to reduce withdrawals, again the American and English rules offer no machinery for accomplishing this. The correlative rights rule would first stop those exporting from the basin, then prorate the available supply among the overlying landowners. Prior appropriation calls for shutting down the junior wells. This might not always work, since there is no assurance that, if a junior stops pumping, the water will move to a senior well. What may be needed is proration or rotation, perhaps giving seniority effect by allowing the earlier wells a larger share or longer pumping period.[40]

In some areas, recharge is so slight that the annual flow of benefits from it is small in comparison with those from the water in storage, and a decision may be made to "mine" the water, to extract the stock for present benefits just as we do with other nonrenewable resources such as oil or coal. The ownership rule places no restrictions on withdrawals in this situation. The reasonable use rule might be construed as requiring pumpers from deep wells who export the water for high values to compensate overlying low-value users when the pumping costs exceed the agricultural values produced. But neither of these rules would prevent a race for the water and a disastrous exhaustion of the resource. The California rule might do so if the court were to hold that pro rata sharing could be interpreted to give each landowner the ownership of a specific quantity of the extractable water. Prior appropriation looks inconsistent with groundwater mining at first blush, since each new well will theoretically injure the first one by hastening the exhaustion of the aquifer. But the courts have refused this literal view of priority and handle groundwater mining quite well. They have approved administrative schemes that place a time dimension on the water right and limit the rate of withdrawal and the number of water rights so as to prevent a race and keep the aquifer producing for a sufficient number of years to permit amortization of investment in water-using equipment and enterprises.[41]

WATER ORGANIZATIONS

Every person is a water user, but very few have "water rights" to stream water or groundwater. An intermediary stands between most consumers and the source, an organization that withdraws water in wholesale lots and distributes it at retail. The distributing agency has water rights that govern its relations with others who have rights to the source, but another type of law regulates its relations with its customers. Urban organizations are usually different from rural, but each may be either public or private. The city dweller is typically served by a public utility company or the municipality itself; the irrigator by a mutual company or some form of public district.

The public utility, or public service corporation as it is often called, is a private firm organized for profit, but one that holds special privileges granted by the state.[42] It has a franchise to use the public streets for its pipes, it usually has a monopoly, and it has powers of eminent domain that enable it to acquire water and water rights by forced sale, if necessary, upon payment of just compensation fixed by a court. In return for these public powers it surrenders some of its freedom. In most states, a water utility must have a certificate of public convenience and necessity, a license to enter the business, granted by the state public service commission. It cannot choose its customers, it can be compelled to render service (within the limits of its water supply) to all consumers within its service area, it cannot discriminate between its customers by giving special rates to some, and it cannot discontinue service, even by going out of business because of unprofitability, without permission from the commission. Most important, its rates and charges are subject to regulation. Rates are fixed to cover operating expenses, including depreciation on its properties and a fair return on the value of the property devoted to public use.

Today most cities and towns engage in a mild form of socialism and run the local water business as a municipal service.[43] Like the public service company, the city must serve all persons and firms within the corporate limits on an equal basis at fair rates. Only a few states subject the cities to public service commission regulation; in most, the citizen who feels abused must seek a remedy in court. Much litigation arises out of service to consumers outside the city limits. Generally, a city may supply such people and industries, but it cannot be forced to do so. If a city undertakes to serve some outsiders, it will not be allowed to discriminate against others similarly situated, but this obligation cannot be enforced to the point that service within the municipality is jeopardized. The city is generally free to set its rates to outsiders by contract, at what the market will bear, and not infrequently the cities, trading on their monopoly position, exact terms not germane to water supply or distribution, such as requirements that the residents of the area accept other city services or agree to annexation.

The main rural water suppliers are the irrigation companies and districts of the West.[44] The earliest needs to combine capital and effort to build dams and large canals serving many farms were met by some form of the mutual water company, a corporation whose shareholders are also its customers. Its capital may be obtained from sale of stock or by borrowing, and its income is usually derived from an assessment on the shareholders based on costs of operation and maintenance. The mutual ditch is now largely replaced by the irrigation district, the rural equivalent of the local street and sewer districts in urban areas. The district is a public body, an arm of government, established by a vote of the residents and landowners within it. Formed by majority vote, it offers one distinct advantage over the voluntary company—minority voters cannot opt out. It is usually financed by a bond issue; its income takes the form of assessments against the improved property large enough to pay principal and interest on the bonds and cover current operating and maintenance costs. Since it is a public agency, its assessments are liens against the land and are collected like taxes. Many irrigation districts cover federal Bureau of Reclamation projects and do not build the works but collect for the Bureau the repayment obligations of the irrigators and the annual maintenance costs. A larger form, the conservancy district, covers a wider area, can include cities and towns, and may collect small *ad valorem* taxes as well as assessments. In this fashion some of the costs of the project are borne by taxpayers in service and supply businesses that receive secondary benefits from economic activity induced by the project.

GOVERNMENTAL, PUBLIC, AND ENVIRONMENTAL RIGHTS

FEDERAL POWERS AND PROGRAMS

Although the Constitution of the United States does not contain the word "water," the Founding Fathers provided for a strong nation, and the powers they gave the federal government have enabled it to engage in many water-related activities and to undertake the most extensive program of water resources development in the world. The national interests served by the federal water resources programs and laws are those inherent in the word "nation"—the use of the country's waters for the free flow of trade and travel between its different sections, the strengthening of the country both internally and in its relations with foreign nations, and the conduct of its national business. The Constitution gives the federal government powers to control commerce, provide for the common defense, make war, enter into treaties, control compacts between states, manage federal property, and raise taxes and spend money for the general welfare of the country. All of these have been used to justify water regulation of water-resource developments.

The most important source of federal jurisdiction over water arises from the power "to regulate Commerce . . . among the several States."[45] It was early held that "commerce" includes "transportation," which in turn includes "navigation." The power to regulate navigation includes the power to control navigable waters, to improve their navigable capacity, to protect them with flood-control projects, or to destroy them by dams. Powers to obstruct or prevent obstruction lead to powers to license obstructions and to the power to generate electricity from the dammed water.

The federal program based on this power is the most significant factor in modern American water regulation and conservation. Huge multipurpose projects combining features of navigation improvement, flood prevention, power production, irrigation, and recreation encompass entire river basins. The federal power over navigable waters reaches far upstream to the nonnavigable stretches and tributaries whose use could affect downstream navigation.[46]

The Constitutional provision giving Congress power to dispose of and regulate the territory and other property of the United States was used to justify the Reclamation Act of 1902,[47] since that Act improved public lands and enhanced the desirability of their settlement. The war power is not often used to justify water development, but in 1916 Congress authorized the construction of the dam that was to become the first unit of TVA, one of the purposes of which was to provide nitrates and other ammunitions.[48] The treaty power governing the international relations of the country has led to agreements relating to the rivers and lakes that form the borders of the nation or cross its boundaries.[49] Pursuant to these treaties, the United States maintains "agreed-upon international lake levels, constructs reservoirs on boundary rivers, and operates projects within its own territory" to carry out treaty obligations to deliver water to neighboring countries. Today the general welfare power is perhaps most important. This is the spending power—the power of the purse; it gives Congress authority to construct any water project that in its opinion will promote the general welfare. It is no longer necessary to demonstrate that a specific power such as navigability is being exercised, and a project may include for its own sake a feature of flood control, irrigation, production of hydroelectric power, supply of water to municipalities and industry, and protection of fish and wildlife habitat and water-based recreation, as long as some national purpose is served rather than a mere local advantage.[50]

In addition to physical projects, the United States has long had programs that encourage and assist water development and use by the private sector and by local governments and public agencies. The Soil Conservation Service channels technical assistance and machinery to individual farmers. The Agricultural Conservation Program adds cost-sharing assistance to individuals and community groups for many types of water utilization, which may include individual irrigation systems and farm works. The Small Watershed Act fills the gap between these programs, which emphasize land treatment and small structures, and the program of the Corps of Engineers, which emphasizes large dams on the main streams. The Farmers Home Administration provides credit, grants, and technical assistance to rural groups for developing community water-supply and waste-disposal systems, while the Department of Housing and Urban Development contains the Community Resources Development Administration, which gives planning, technical, and financial assistance for the construction of new water and sewer facilities. The Department of Commerce, through the Economic Development Administration, provides financial assistance to governmental and nongovernmental projects that will stimulate employment and increase income in depressed areas. The Bureau of Outdoor Recreation coordinates and develops programs under the Land and Water Conservation Fund Act for planning, acquiring, and developing outdoor recreation facilities; and the Bureau of Sports, Fisheries and Wildlife is a large water user in its maintenance of wetland habitat and irrigation of wild and domestic range for ducks and other wildlife.[51]

One major feature of federal water law is its superiority over state law. Federal projects are not restricted by limitations imposed by state law.[52] Their water rights are superior to private appropriations or riparian rights. If private rights must be taken over for or destroyed by a federal project, all the owner can demand is compensation,[53] and not even that if his rights attach to a navigable river and were always subordinated to the "navigation servitude," the federal overriding power.[54]

If drought and climatic change call for "engineering solutions" to prevent potential harm or to rescue cities, industries, and public activities that have already received the blow, these national powers and programs will probably provide most of them. The problems are likely to be national or at least regional in scope and will call for national solutions. More storage will call for huge dams, which only the federal treasury can finance. Transmountain diversions and interstate or interregional transfers of water will call for federal powers to countermand local laws that establish in-basin preferences or attempt to fortify interregional jealousies. And when "importation from a water-rich area" reaches its ultimate dimension and the United States begins seriously to consider approaching Canada for some of its surplus, the national powers over foreign affairs will be called into play.

RESERVED RIGHTS, INDIAN RIGHTS

By virtue of a series of cessions and treaties, the federal government at one time or another has been the owner of practically all the land west of the Alleghenies. Until fairly recently, the major policy behind the public land laws was one of disposal, and the United States gave away or sold as much as it could to settlers, miners, railroads, and states. Occasionally, it reserved land by withholding it from the operation of the land laws and used it for military reservations, Indian reservations, national parks, national forests, and wildlife areas. In 1908, the Supreme Court held that when the government set aside an Indian reservation it also reserved from appropriation enough water to accomplish the purposes of the reservation, enough to irrigate the land so the Indians could change from nomadic hunters to farmers and ranchers.[55] Reserved rights are an exception to the rule of priority, they are dated as of the founding of the reservation (some tribes may have rights that go back to prehistory), they exist whether used or not, and they may be called into play at any time. They are measured by the quantity needed to irrigate all the arable land on the reservation,[56] and perhaps, although this has not yet been decided, enough additional to develop all minerals and accomplish any other modern objective of the tribes. When they come to be used, these Indian rights will have the first or one of the first priorities on many western rivers. They will, therefore, be the rights least affected by drought.

In 1963, the Court held that these rights attached to other types of reservations.[56] Many uses for parks or campgrounds will be minuscule, but some for wildlife areas or to maintain free-flowing streams in national forests may be large. Reserved rights add considerable uncertainty to off-reservation appropriations on the western streams, and their eventual exercise will exacerbate the unsettling effects of any long-term water shortage.

STATE'S RIGHTS AND POWERS

While state governments do not often engage in water-using activities or water-development projects that call for water rights like those of other entities, they have been assigned shares in interstate rivers. When total claims in all the states exceed the capacity of the stream, each state is given a share and the water is then distributed to the water users under state law.

The first interstate allocations of water were made by the Supreme Court of the United States, the forum for interstate disputes. Rival states on an interstate stream were said to be each entitled to an “equitable apportionment of the benefits of the river.”[57] In several western cases, the Court has allocated a specific share to an upper state, leaving the rest to a lower,[58] it has forced the upper state to respect the priorities of projects in the lower state,[59] and it has split the water on a percentage basis.[59] In the east, it has limited the size of a new project in the upper state and required a cleanup of pollution and the release of a minimum flow for the maintenance of fisheries and sanitary flows in the lower state.[60]

Interstate compacts provide another method of apportioning interstate water. The Court has trimmed excessive claims to fit the available supply, and it has enjoined or limited new projects in the upper state that would disturb the status quo in the lower, but it has not apportioned unappropriated water. When states wish to settle disputes by agreement rather than litigation or when they desire to fix shares in the unused water for future use, an agreement between them, made with the consent of Congress, is as binding as a decree of the Court.[61]

Interstate compacts have settled disputes, divided unappropriated water into specific shares, approved specific projects, set up operating criteria for projects, and established commissions representing all the states (and sometimes the United States) to handle some matters of future cooperation. When the first one, the Colorado River Compact, was negotiated, the representatives of the seven states involved could not agree on the share each state would receive for its water users, but they did clear the way for the Boulder Canyon Project (Hoover Dam and Lake Mead) by accepting the compromise suggested by Herbert Hoover, the federal representative at the conference, that at least the water could be divided between the upper and lower basins, separated by miles of rocky desert. A dependable flow of 15 million acre feet (maf) per year was assumed, and 7.5 maf was assigned the states of Arizona, California, and Nevada for use below the Grand Canyon, and 7.5 maf to the upper basin states of Colorado, New Mexico, Utah, and Wyoming. This arrangement gave the upper basin states a fund of water immune from priority and allayed the main fear of the people that their eventual uses would be foreclosed by California's earlier development. The lower basin was given a large advantage by a provision that the upper basin would deliver 75 maf in each 10-year period, which places on the upper states all the risks that the flow will not meet the assumed average of 15 maf.

The share of the upper basin was divided in 1949 by the Upper Colorado River Basin Compact, which gave each state a percentage of the basin's water. The lower basin states were never able to agree on such an intrabasin allocation; and, in 1954, Arizona sued California to determine their relative rights. The case was perhaps the largest lawsuit ever tried and was pending for 11 years. The Court did not use the doctrine of equitable apportionment; instead it found that in the Boulder Canyon Project Act of 1927 Congress, by provisions for the management of water from Lake Mead, had allocated specific shares—4.4, 2.8, and 0.03 maf, respectively—to California Arizona, and Nevada.[62] The holding that Congress had power to allocate interstate waters created a third method of so doing, but one that has not been used again.

The states do not have complete control over the water in all cases. In some early suits, the United States asked the Supreme Court to make an allocation to it as well as to the states. This the Court refused, and the states' share, whether fixed by decree, compact, or Congress, must include (and accommodate) water rights for all federal projects, federal reserved rights, and rights of the Indian tribes.[63]

ENVIRONMENTAL AND PUBLIC RIGHTS

Environmental law is sometimes thought of as something quite new and modern, but it has roots deep in the law. In the water field, eastern water law never completely abandoned the natural flow ideal and still places heavy emphasis on preservation of the aesthetic values of “living water” and lake view. The flow of navigable waters is protected from private interference with the “public rights,” the right to use the water for travel and carriage of goods. On the smaller streams sportsmen and pleasure boaters now enforce the public trust to protect values of recreation and conservation in waterways once used by fur traders in canoes or for the log drives of lumbermen.[64] Several states have extended the notion of public water to nonnavigable waters,[65] and some of the permit statutes establish minimum flows, which means that the stream legally goes dry long before it is physically dry.[66]

Western water law was always founded on the notion of beneficial use, and in this century the permit statutes commonly insist that each new use must be “in the public interest.” Officials are beginning to recognize that something that causes more harm than it does good cannot be beneficial and cannot serve the public interest. Several western states now provide in one way or another for instream uses and minimum flows and the preservation of recreational, fishing, and wildlife values.[67]

These are the seeds from which the modern law of environmental protection has grown. Consciously or unconsciously the judges have always accepted the economists' maximization principle—the search for efficiency—that combination of labor, capital, and resources that produces the greatest excess of benefits over costs.[68] The law has not changed; only men's ideas of what are costs and benefits have changed. Benefits are those things that people value, and costs are things that people do not like to lose. Our ancestors, our fathers, we ourselves in our youth were willing to throw away as worthless some scenic, recreational, and environmental elements. Perhaps they were worthless because they were so abundant. Now what is left is far from abundant; it is scarce, partly because we have already thrown away so much of it, partly because there are now so many of us that we compete with each other for what is left, and partly because our opportunities for enjoyment have been broadened by the automobile and the modern highway. Whenever scarce resources are desired by many people, the law of supply and demand produces high values. The decisions we make today are not those that we would have made several years ago, because any time a formula is applied, the result will change if a different value of a variable is plugged into it. It is this change of values rather than a change in the formula that results in the protection given in the new environmental cases.

The change did not come about easily. As substantial numbers of people became aware of environmental dangers and tried to get protection for values that they treasured, they found that their voices were falling on deaf ears. Not everyone shared their appraisal. In the early stages of the environmental movement, entrepreneurs and agency personnel did business as usual and dismissed environmentalists as “kooks” and the movement as a fad that would soon disappear. Unable to get a hearing in the agency offices, the environmentalists went to court. Lawyers did what good lawyers always do and focused all their knowledge on the problem, used all their skills, and brought to bear all the techniques of courtroom and administrative procedure on their side of the dispute. The first real victory for the environmental movement came in the *Scenic Hudson* case, in which it was held that the agency making a decision must at least listen to the environmentalists' side.[69] As the movement enlisted wider public support, Congress passed the National Environmental Policy Act of 1970. In the *Calvert Cliffs* case, agencies that attempted to brush off this Act were told that they must comply with it.[70] In case after case, the Corps of Engineers, the Soil Conservation Service, and many other agencies that do not deal with water have been told that NEPA means what it says—federal agencies must consider in detail the environmental impact of a proposed action, the alternatives that might avoid adverse environmental effects, and any irreversible, irretrievable commitment of resources. They must inject benefit–cost analysis into the decision-making process at an earlier stage and analyze every reasonable alternative to ensure that the project eventually chosen provides the best combination, instead of comparing costs and benefits of a project after it is formulated.[71]

The spectacular “environmental lawsuit” is likely to disappear. Agencies, administrators, and businessmen may have been hidebound, but they are not stupid. They will not continue to butt their heads time and time again against the same stone wall, never changing. They can learn and are learning that a decent consideration of the environment is a necessary part of the process of reaching a resource decision. As this lesson is learned, there is less and less need for long drawn-out lawsuits as more and more the environmental factors are heard and thrashed out at the agency level.

LEGAL CHANGE TO MEET CLIMATE CHANGE

NATURE OF LEGAL ADJUSTMENTS

While it is probably true that most legislation is enacted because a bad situation has arisen and a remedial law is needed, still some is forward-looking, and many laws are designed to prevent harm from occurring. Whether we prepare for drought or react to it depends on the legislative perception of need. Legislators and congressmen are busy men who deal with pressing current problems. They will react swiftly to today's disaster, but they will plan ahead to avert tomorrow's only if they are convinced that a real problem exists today. If it could be predicted with some certainty that within ten years the continental pre cipitation would decrease by 15 percent and remain at that level, we might expect a surge of new water laws that would carry us into the new era with as little pain and disruption as possible. Since the best proposition that can now be set forth is that the climate may change, but we cannot fix the odds that it will, and that droughts of sharper intensity and longer duration than those we have known are possible but we cannot evaluate these possibilities, then less immediate and forthright action may be forthcoming. One difficulty is that almost by definition our problem has some elements of unreality. Our concern is with unpredictable change. The problem is similar to some others we face: whether we should refuse to license atomic reactors because there is one chance in a million that one might explode, whether we should prohibit the manufacture and use of aerosol deodorants because there is one chance in 10^n that they might destroy the world's ozone layer, whether we should ban a food coloring that induces cancer in mice and “might” induce cancer in men. The law handles matters like these all the time, prohibiting or imposing liability for high-risk enterprises even though damages might be small in each case and for low-risk enterprises when a single occasion could cause enormous damage, whenver the product of risk times harm is sufficiently frightening.

Even if a climatic change occurs, an immediate legal reaction is not certain. There will still remain a question of perception. When will a gradual change be recognized as a drought? How long before a series of bad years will be sensed as a change in climate? In the third year of a drought will we be able to see that it is the third of ten? There is a real possibility that we will muddle through with our present laws. We have at least glimpsed what would be in store for us if these were used to handle change. Not all the consequences would be bad, but there are some dangers that uncontrolled action could worsen the situation and that sensible adjustments could be blocked or made unnecessarily difficult or expensive. Yet some laws at hand for handling shortages would do very nicely for drought.

It is more likely that if a climatic change does occur the lawmakers will see the inadequacies of existing laws and will act to remedy the ills and patch up the damage. Even short-term droughts have done wonders for the cause of water law reform.

Of course, it is quite possible that legislators might act in advance and be ready with laws on hand to handle drought and change when they occur. Since the improvements needed are of the same nature as those desired for other purposes, the unpredictability of supply may be used to reinforce the movement already on foot to prepare for the predicted increase in demand. Much of what is needed is simply improved water law. Much improvement will take the form of following the example set by laws in force elsewhere, and much will simply continue existing movements toward better laws. Uncertainty of supply, if brought home to lawmakers, could accelerate a trend already in motion.

THE DIRECTION OF LEGAL CHANGE

Since the solutions to legal problems created by less water are either engineering or economic, a law that facilitates these solutions must paradoxically combine features of both certainty and flexibility—certainty to encourage investments in projects and flexibility to permit shifts of water between users and uses.

In the field of water rights this is really not too difficult, and the western appropriation, a definite, easily enforced but transferable right, comes close to filling the bill. The security needed to finance long-term projects is there, and interim adjustments can be made between uses so that the most valuable survive and the least productive are discontinued. But these adjustments are not easily made, and unregulated trading in property rights sometimes causes serious loss to third persons or harm to the public. So what is really needed to improve appropriation law is to tighten up yet speed up the regulatory process so the market can operate smoothly and quickly without these injurious side effects.[72] One such effect is reflected in the rule that a change in use must not injure other appropriators. In practice, this means that an irrigator cannot sell his gross water right, his total diversion, since his crops do not consume all the water and downstream users are dependent on the “return flow.” A hearing must be held, complete with conflicting expert testimony, to determine how much can be sold, and permission to make the change may be denied on guesses as to probable effects. If all rights were redefined from terms of diversion to terms of consumptive use, if formulas for calculating consumption were improved and applied automatically, if trials and experiments were allowed to determine the actuality rather than the probability of harm or no harm, the process would be vastly improved.

Another needed addition would facilitate interim and short-term adjustments. Most changes and sales are of water rights, permanent property rights, good for water this year and every year. This fits many needs, but there is also need for sales of water as a commodity. One state recently attacked this problem by allowing the “leasing” of water rights.[73] In a water-short year, a bean grower who anticipates a high price may buy the water of a potato grower who foresees a glutted market. A city faced with unusual drought may buy a season's supply to tide it over instead of a permanent right that will go unused in most years. Similar rights may be needed in many states.

It is obvious that riparian law has little to offer. As supplies dwindle and demands increase in a riparian law state, withdrawals and consumptive uses will become more obvious and create more conflicts, more need will arise for adjustments and share fixing, and more complaints will be made of nonriparian uses. In-place uses for the amenities and site values are bound to suffer. New users will cut deeper into supplies already in use and will find themselves facing suits more often. Storage and importation are risky, and attempts to purchase water, water rights, and freedom from lawsuits involve complex, mul tiparty, expensive negotiations. The lawsuit is too slow and expensive to handle these conflicts on a large scale.

As the field for new uses narrows, there is more need for administrative controls. Those states with permit laws have made a beginning, but drought would bring out the need for better identification of rights and determination of permissible action, more certain rules of who will get how much water in times of shortage, more stability of tenure and investment in water-control works and water-using enterprises. Nonriparian uses should be legitimatized, and limitations of uses to riparian land or single watersheds should be recognized as uneconomic and abolished.[74]

A better method of achieving flexibility should be found. The bureaucratic shift of water “to its highest and best use” by canceling and juggling permits has a surface appeal, but it must be remembered that laws regulate not water but people, who may be farmers, stockholders in a manufacturing company, or householders in a city. Water and money are for the most part interchangeable, and what we really mean by “shifting water from existing uses to better uses” is enriching some people and impoverishing others. When this is better understood, a change to a system under which the gainers pay the losers seems likely. Administrative action is usually needed only when we have “market failures,” “externalities,” and “social costs.” A water market should be regulated to avoid these, but when it works, it works better and more efficiently than a government agency. The bureaucrat trying to decide the best use of water as between agriculture and industry will have to investigate, hold hearings, hire experts, finance a university study, and make findings. The manager of the Tootsie Textile Company and Farmer Jones, sitting at the bargaining table, can tell the answer in a minute by a glance at the bottom line of last year's books.

All this, of course, would be a movement toward the western appropriative right. For some reason easterners do not like prior appropriation; for them it still has some connotations of a Wild West rip-off of the public domain. But in a modern controlled situation, priority is not a grant of special privilege, it simply means that the state, having granted the water to one person, will not grant that same water to another. On a fluctuating source, priority is a necessary element of a right, one that marks its boundaries and limits new grants to water that is available in nature and not already committed to someone else's existing use. Sometimes sharing of short supplies among similarly situated persons such as farmers may be desirable, and within a single project is possible, but even then the rights of the sharing group must be differentiated from those of other groups or users.

Somewhat similar directions can be assumed for groundwater. In the eastern states, a long-term drought or change would be likely to cause a sudden strain on groundwater, since in many areas a move to it will offer the quickest and cheapest method of augmenting a dwindling surface supply. Safe yield, water table, and mining problems could move eastward as the effects of long-continued drought move underground. Unregulated development, if it occurs too fast, could require cutbacks in pumping and abandonment of wells. Decreased supplies and increased use will probably hasten the shift of law away from “ownership” rules to regulation of withdrawals and allocation of shares. Economic solutions to groundwater shortage will call for some variation on the themes already played. The best form of groundwater right where the water is a “flow resource” is a rule of priority that divides the recharge into specific shares and that limits the number of shares to the available supply. If the water is a “stock resource” being mined, apportionment of a specific quantity of water to each claimant is probably the ideal solution.

One legal change much advocated by economists is the improvement of institutional arrangements so as to enable a pricing policy to operate as an incentive to ensure utilization of water at the most efficient level.[75] Most water can be withdrawn from the source for free: the western appropriator pays nothing when he opens his ditch; the riparian proprietor, the overlying landowner, the city can turn on a pump with no charge other than for electricity. But if water were properly priced, we are told, there would be more water to go around since waste would be avoided; and when the source diminished, the reduced supply would generate a higher price and water would move naturally to its highest and most economical use. The English have such “charging schemes” set up under which a landowner must pay for exercising his riparian rights or pumping from his own well, but the notion is not a popular one in America.

More hope for water pricing as a solution to reduced supplies of water might be held out for improvement of the pricing policies of the distribution organizations that now sell water. Usually their prices are fixed with no concern for demand or encouragement of economy. Mutual irrigation companies assess their shareholders for current operating costs, irrigation districts levy assessments on the same basis plus debt service and retirement. Municipalities and metropolitan agencies similarly look to recapture of costs rather than to value of water in fixing charges, and public utilities seek a fair return on and amortization of their investment. Unless water is subsidized, it must pay the cost of producing it, of course, but it might be desirable to have this its minimum price and set the going rate so that demand at that level just equaled the supply. Pricing could function in this fashion whether demands increase or supplies diminish; water would serve its most valuable (efficient) uses. Before this could happen, most laws authorizing and regulating water-supply organizations would have to be modified.

Federal water law might need to change very little. The United States is the world's largest engineering and construction firm and will probably supply most engineering solutions. The federal government has ample Constitutional powers for handling climatic change and drought. New federal projects and stepped-up programs will be needed for most rescue or preventive operations, since local and private measures will run into financing difficulties and legal restrictions, such as against transdivide diversions.[76] But except for project and action authorizations and appropriations, little new federal law seems needed. If the nation wishes to prepare for the possibility of drought or change, it might be wise not to now build dams and facilities with excess capacity that might stand unused as monuments to folly but to eliminate much of the time lag usual in federal projects by having on hand a backlog of standby projects engineered on the basis of our best guesses, ready for immediate action when needed.

From the national point of view, it could be found that some interstate decrees and compacts that allocate shares of rivers to states have confirmed or authorized uses that are not the best. If stream flows decrease, some states with specific plans for their shares of unused water may find the reduced amounts too small. A long-term drought could trigger attempts to renegotiate the compacts or seek congressional action to reallocate the water and redivide the rivers. It is not expected that this would be an easy process, and engineering solutions by importing water may be more attractive.

A very difficult problem facing the West could be made doubly difficult by a decreased supply. When Indian reserved rights become fully exercised for irrigation and mineral development, a number of persons now using water off the reservation will suffer a loss of their water.[77] There could be an extensive reduction in land values, income, and area prosperity. The dislocation could be intensified if white owners of water rights are squeezed from the top by native-American claims and from the bottom by reduced stream flows. Some engineering solutions are possible where storage could firm up both white and Indian rights. Economic solutions involving payment to Indians may not be available, since the Indians have had poor results from selling their lands and they may need water to maintain their cultural base and their homelands. Another possibility has been suggested: the United States should regard this as a national obligation and include compensation to displaced off-reservation users as a part of the cost of future Indian projects. Some object to this as payment for the return of stolen property and as increasing the costs of Indian projects, but it might make those projects more politically feasible, and it might be remembered that it was not the present water users but their father's father, or their predecessors in title, who “stole” the Indian's water.

Environmental pressure to save streams from development and preserve amenities may increase but may be offset by increased demands for withdrawal and storage. As man's demands increase and nature's supply lessens, all water will become more valuable. If population pressures and industrial growth send municipal and industrial demands skyrocketing, then some features at the lower end of the environmental scale, which are protected today, may be sacrificed in the future. On the other hand, as less water and more development make free-flowing streams more and more rare, the aesthetic, recreational, and ecological value of the remainder will shoot up, and we may tell cities and industries to tighten their belts, sharpen their efficiencies, and recycle their present supplies. This is an economic process, although not always performed in the marketplace. While we pay for some recreational experiences and sometimes combine the interests of many into private organizations that can compete for water in a sense, we prefer that most of the matters we call “environmental” be provided as a public good, and we seek legal solutions by political processes rather than economic solutions dictated by market forces.

To sum up in a single sentence: If our climate should change for the worse, our water laws should change for the better.

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[Note: Most of the legal rules stated in this chapter are generalized statements distilled from a number of cases or derived from the trend of decisions. The citations in these notes are to typical, illustrative, or “leading” cases. Differences in fact situation, variations in statutes of different states, and disagreements between courts of different states can add enormous complications. Most of the cases cited here and many of the variations on these themes can be found in F. Trelease, *Cases & Materials on Water Law,* 2d ed. (West Publishing Co., St. Paul, Minnesota, 1974), a student textbook. The bracketed references to “Trelease” following the official citations are to pages in that book.

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5

Identification of Economic and Societal Impacts of Water Shortages

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INTRODUCTION

Water-supply planning and design technology has as its basis the assurance of the adequacy of the source of supply and the distribution system in meeting customers' water requirements. Operating experience of water-supply systems indicates that these systems at times fail to provide the water demanded by their customers and, thus, subject them to water shortages. A water shortage in this sense has been defined as occurring at any time a water purveyor chooses, or is forced into, a position in which he cannot supply all the water demanded in the system (Young *et al.,* 1972). No water-supply system is ever totally free from the possibility of experiencing water shortages.

Water is vital for plant and animal life and is a necessary part of many industrial processes and our present standard of living in the United States. Water is such an integral part of modern society that its availability is virtually assumed by the consumer in whatever quantities he may desire. Drought is one of the common natural disasters to which man is subjected (White and Haas, 1975). Reduction in available water results in effects ranging from inconvenience to serious economic loss. Although irregular, periodic shortages are possible in every water supply system, there is little quantitative or even qualitative information available concerning the effects of water shortages of varying magnitude and duration on water users. In most cases, both the water utilities and users are so relieved when water shortages pass that they try immediately to forget actions taken and losses incurred rather than to document them.

Climatic change producing a reduction in water available in a particular region can result in periodic or continuously occurring periods in which water available for use is not sufficient to meet water requirements. Periodic or continuously occurring water deficits certainly will result in different responses by different water users. However, in this paper, primary attention is addressed to effects of periodic water deficits, as this is the only type of water shortage on which any information is currently available.

People are adaptable and alter their actions in response to environmental conditions. Some shortages can be tol erated and overcome by using simple conservation measures. However, as the magnitude of the shortage increases or the duration lengthens, losses and deleterious effects from the shortages increase. This paper seeks to outline and describe the effects of water shortages upon the various users. Data were drawn from newspaper articles, private communications, research reports, and monographs. Additional in-depth research is needed to develop the methodology necessary for water-systems planners, designers, and managers to be able to evaluate the importance of potential shortages on designs and operating plans.

TYPES OF WATER SHORTAGES

Water shortages occur with varying frequency, duration, and severity. In the study of which this paper is a part, attention is being focused on the impact of possible future climatic changes on water availability and subsequent use. Lofting and Davis (see Chapter 3) provide insight into methodologies for predicting water requirements. Reductions in water availability resulting from climatic change can be expected to be gradual, resulting in a steady decrease in water available for use. This comparatively long-term reduction in water availability undoubtedly would result in changes in the water-use characteristics in a region. Depending on the magnitude, frequency, and duration of shortages that occur, certain permanent changes in the water-use patterns can be expected to occur. Persons may move away from the region. Water-reuse systems may be installed in industries. Additional diversion works, wells, aqueducts, and storage reservoirs may be constructed. Residential-use patterns may be altered by permanently adopting conservation measures.

Water distribution systems almost always are subject to the probability of a water shortage occurring. Water shortages can be produced by a variety of causes. Some of these are as follows:

1. Deficits in raw water supply.
2. Inadequate distribution systems.
3. Improper operating policies of management agencies.
4. Growth in demand.
5. Improper pricing of water.
6. Catastrophic damage to facilities.

The primary concern in this paper is with identifying possible economic and societal impacts resulting from reductions in raw water supply caused by climatic variation. Droughts and water shortages often have been experienced through variation in climatic conditions in a portion of the country for specific periods of time. However, no clearly defined evidence of long-term climatic change has been identified at this time. Thus, this paper will focus on identifying effects and problems illuminated as a part of water shortages that have occurred in the past.

ACTIONS TAKEN DURING SHORTAGES

Reductions in water availability that generate water shortages result in actions being taken by the utility management to reduce water use. Immediate measures as outlined in this section are ordered to bring about short-run reduction in water use. Frequently, longer-term actions are begun, including construction of reservoirs and aqueducts, increasing water rates, or changing operating policies. An idealized description of this process is shown in Figure 5.1, as described by the Institute for Water Resources (Young *et al.,* 1972).

Experience with water-shortage situations in the past indicates that few utilities have concrete plans available for dealing with water shortages as they develop. This failure to have adequate operating plans available is often made worse by the failure of the management of the city or utility to act decisively before a full-scale shortage is in existence. Case studies describing actions of water utility management in the past are contained in a subsequent section of this paper. There is a natural tendency for managers of agencies to delay action in an effort to minimize the impact and inconvenience upon consumers. Some agencies have proposed specific plans for dealing with water shortages (Water Resources Engineers, Inc., 1975).

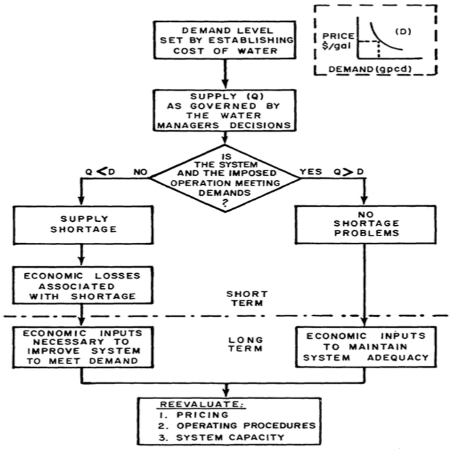

FIGURE 5.1 System evaluation of shortage.

Various immediate actions can be taken in the event of a water shortage. Often because of the delay in taking early action, measures of the type listed below must be taken in rather rapid succession. The purpose of each of these measures is to reduce water demand. A graphical description of demand reduction possibilities drawn from the report of Water Resources Engineers, Inc. (1975) is shown in Figure 5.2. The possible numbered actions are as follows:

1. Reduction of water use by voluntary conservation.
2. Restriction on outside use of water (sprinkling, etc.).
3. Mandatory reduction in water available to industrial and commercial establishments.
4. Complete shutdown of industrial and commercial usage.
5. Severe restrictions or cutoff of residential users.

Customers of water utilities have been known to accept drastic reductions in water available to them if they have adequate explanation of the reasons for the crisis and are convinced that every possible action to alleviate the crisis is being undertaken. In the next section, examples of the types of consumers and the effects of water shortages on them are presented.

TYPES OF CONSUMERS

Water users may be classified in a variety of ways. However, for the purpose of this paper, major users will be considered subdivided into the following categories: (1) residential; (2) industrial; (3) commercial; (4) other (municipal, governmental). Water curtailments are generally distributed among the various water users unevenly. Indication of the effects of these curtailments are described in the following sections.

IMPACTS OF SHORTAGES

Water shortages affect classes of users in different ways. Furthermore, effects of water shortages can be categorized as economic (monetary losses) or social (human welfare). In this section, economic and social effects of water shortages on classes of consumers will be presented and discussed.

ECONOMIC EFFECTS

The monetary losses resulting from water shortages can be classified as follows:

1. *Residential:* Monetary losses are experienced in the form of horticultural damage to lawns and shrubs. Costs are also incurred because of failure of plumbing and increased costs of water (e.g., purchase of bottled water).
2. *Industrial:* Losses are felt because of reduced value added by manufacture plus reduction in payroll due to employee layoffs.
3. *Commercial:* Tourism (motels, hotels) is affected and water-oriented firms (car washes and laundries) sometimes fail.
4. *Other:* Water utilities often lose revenue and experience increased cost because of purchase of trucked water or construction of emergency facilities. Recreational facilities (pools, etc.) may be closed, and governmental productivity may be affected.

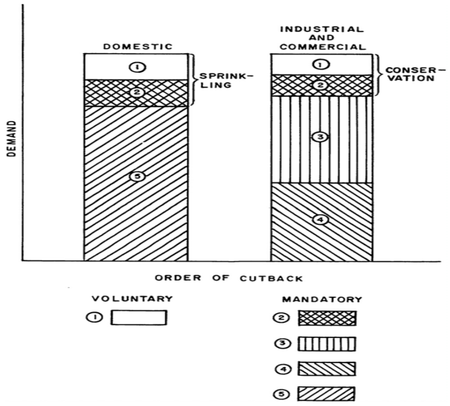

FIGURE 5.2 Demand contraction.

A graphical description of the interconnection between the users in a water shortage situation drawn from Young *et al.* (1972) is given in Figure 5.3.

SOCIAL EFFECTS

Social effects of water shortages may be broadly considered as the impact of the shortages on human welfare. There is little information on which to draw in this area. Reductions in water availability obviously affect the lives of individuals living in the area in many pervasive ways.

Analysis of the social impact of water supply reductions requires that one develop a model of the social system. Other investigators (Water Resources Engineers, Inc., 1975) have enumerated the elements of the social system as the governmental institution, commerce and industry, family, education, religion, community, culture and art, leisure and recreation, health and safety, and housing.

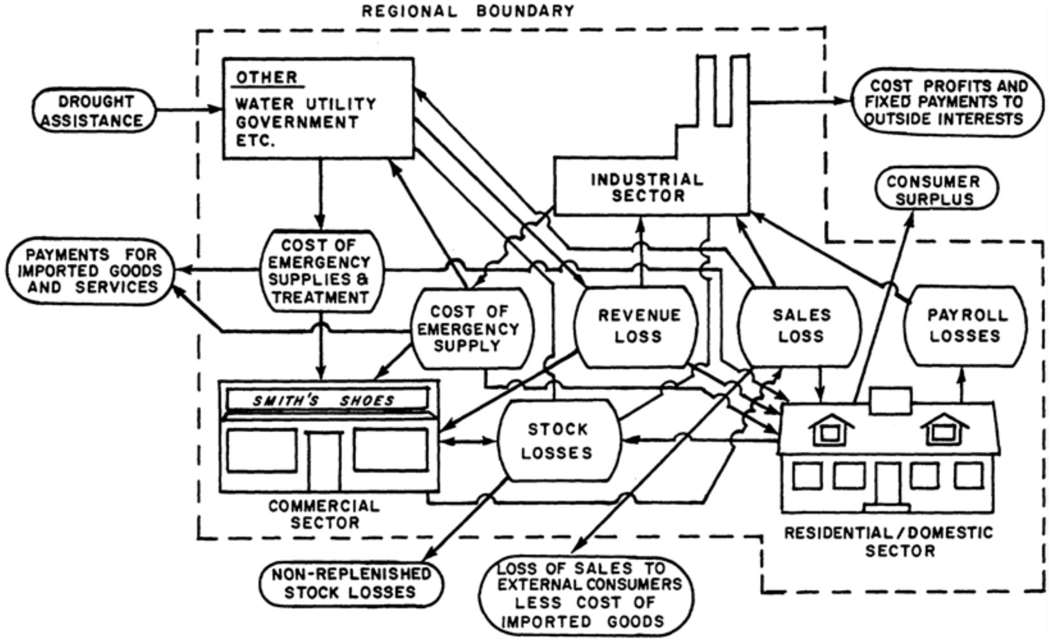

FIGURE 5.3 Water shortage loss balance.

Development of a model of the social system requires identification of the groups and institutions being differentially affected. It is important to identify the dynamic interrelationships existing between these institutions and groups. For example, reduction in water available to recreational facilities (golf courses, pools) impacts the family and industry supplying leisure equipment and supplies. Efforts to develop computer simulations of social systems have not yet reached the stage of providing the capability necessary to conduct quantitative analyses. This remains a fruitful area for research. In order to make realistic social impact predictions, the measures of potential deficits must be coupled with scenarios of their impact on society. Although quite important, this must now be qualitative.

Social impacts include many aesthetic and intangible considerations. Changes in taste and odor are experienced when waters of different quality are introduced into the system. Public concern and indication may be aroused when alternate sources of supply are considered to be "polluted." Examples of these instances will be given in the following section.

EXAMINATION OF CASE STUDIES

Several cities have experienced damaging water shortages in recent years and furnish potential laboratories for research. Some of these are York, Pennsylvania (Young *et al.,* 1972); Braintree, Fitchburg, and Pittsfield, Massachusetts (Russell *et al.,* 1970); Dallas, Texas (Bolding, 1975); Trenton, New Jersey (*The Evening Times,* 1975); the Delaware River Basin (Cyphers, 1976; Hogerty, 1970); and the Washington, D.C., metropolitan area (Water Resources Engineers, Inc., 1975). In this paper, the Dallas, York, Delaware, and Trenton experiences are summarized. The Dallas drought experience illustrates citizen responses to shortages and water-quality variations that occur when alternate supplies are used. The description of the drought experience in York provides actual data defining economic losses. In the Delaware situation, legal and institutional problems occurring between sates during water shortages are discussed. Problems occurring in Trenton illustrate the importance of the water-utility management in having contingency plans for water-supply emergencies. The report describing effects of deficits in the Washington, D.C., area attempts in a pioneering way to identify social effects of various levels of water deficit. It was not possible to draw substantive conclusions from this report regarding social effects of deficits. Thus, this information is not summarized in these case studies.

DALLAS, TEXAS

The Dallas Public Utilities during the drought of the 1950's in Texas found themselves with more mud than water in Lake Dallas. Immediate plans were made to seek alternative sources of water. Two emergency sources of consequence were available. These were the West Fork of the Trinity River, a stream carrying municipal return flows and known for its pollution load, and the Red River, which separates Texas and Oklahoma and is of poor inorganic quality. Red River water can have up to 3000 mg/liter of sodium chloride during low flow periods and several hundred mg/liter of sodium chloride during high flow periods.

The utility favored pretreatment of West Fork Trinity water in lagoons followed by complete treatment resulting in both potable and palatable water. To make use of Red River water, a pumping plant and diversion facility would have to be constructed to pump water over a ridge some 350 feet high into a tributary of the Elm Fork of the Trinity River for subsequent use. The public, refusing to accept drinking “polluted” water, supported and gained acceptance for use of Red River water even though it was considered to be of inferior quality by the utility.

In an effort to sway public opinion, the Dallas Water Superintendent publicly drank water from a bench-scale pilot plant demonstrating the usability of the Trinity River water. However, this effort failed. In addition, abandoned water pumping plants on small streams in the area were reactivated, and wells were drilled to depths of 2700 to 3200 feet to secure additional water.

By the mid-1950's, water supplies continued to dwindle to the point that conservation measures were introduced. Water was rationed in response to ordinances passed by the Dallas City Council, which called for water sprinkling on alternate days by even and odd numbered houses. Water use continued to be restricted, with more drastic restrictions introduced as supplies continued to diminish. Some businesses drilled shallow wells into water lenses lying 15 to 20 feet below the surface of the ground, which provided small quantities of water. These waters were used in some instances to operate small businesses such as car washes and to sprinkle lawns in residential areas.

For the most part, the public was very cooperative. The water utility released information to the news media to keep the public informed as to the reasons for conservation measures and changes in water quality and taste. However, numerous real or imagined complaints due to deteriorating water quality and taste were received by the utility. Problems included inferior taste, horticultural damage, increased service requirements for water-using cooling equipment, effects of water quality on persons with diet problems, and damage to plumbing.

Water shortages were experienced by citizens for approximately 6 years. Economic costs and losses, although not quantified, were experienced by water users. The degree to which perceived losses actually were related to the drought is as yet unproven. Losses were caused both by reduction in the supply of water and by changes in the quality of the water.

Horticultural damage to lawns and shrubs was experienced. Because of the salt content of the Red River water, which was highest during the summer months, losses to salt-sensitive plants such as gardenias, azaleas, and camellias was reported. Others reported loss of lawns or plants because they either could not sprinkle enough or had a highly mineralized supply. Deep-watering irrigation principles had to be learned by the citizens. Other citizens with private wells and fine lawns displayed signs noting their lack of use of city water.

Other economic losses resulted from use of the highly mineralized waters. Plumbing damage was experienced, and it caused many unhappy water users. Because of the good-quality water available prior to the drought, most piping was wrought iron and water heaters were galvanized. Water heaters often lasted at least 7 years and sometimes as long as 17 years. In some areas, hot well water devoid of oxygen was in use. Thus, plumbing was not built to withstand corrosive waters. When sources of water supply changed, plumbing failure and ensuing large plumbing bills were experienced.

Evaporative coolers with recirculating pumps, which were in widespread use, began for the first time to require frequent service and cleaning. Many people who were unaccustomed to cleaning their coolers found pans filled with brines and fiber mats fouled with minerals.

Taste and odor problems were significant and caused many complaints. Some were traceable to changes in water quality, while others resulted from the use of waters subject to warm-weather algal blooms. Furthermore, the Dallas County Medical Society was kept apprised of the mineral content—particularly the sodium content—of the water for use by patients who were sensitive to changes in mineral content. Bottled water became a primary source of drinking water for some persons in Dallas. Some of the bottled water sold in local grocery stores was shipped from spas in Arkansas and was more highly mineralized (in sodium, for example) than was the Dallas water supply.

Water with foul odors was also produced in water heaters when there were changes in the water-supply source. Ceramic-lined water heaters were placed in some sections of the city with cathodic protection in the form of magnesium rods. These magnesium anodes were sized for the Dallas surface-water supply and when well water was used had to be removed because of the reduction of sulfites in the well water to sulfides in the absence of oxygen.

The public cooperated fully with the utility, recognizing the seriousness of the situation. The utility worked to keep the public informed, and the information supplied was useful in stimulating cooperation. (The author is indebted to M. E. Bolding of the Dallas Water Utilities for this information.)

YORK, PENNSYLVANIA

The City of York, Pennsylvania, is situated in the south-central part of the state. The York Water Company, which serves the area, is a privately owned enterprise. More than half of the income in the area served by the water company is derived from industrial and commercial sources. The shortage considered herein occurred in 1966 and was part of the general drought that afflicted the northeast of the United States at that time.

During the four years preceding 1966, precipitation had been below normal. Winter snowfalls had been light, and unusually cold winters resulted in deep ground freezing and high spring runoff without significant infiltration to the ground waters. Total precipitation in March through May 1966 was 25 percent below normal. Because there was almost no rain in June, water demands were high. By June 13, the company had to begin drawing upon reservoir storage. Conditions worsened in late June and early July with near record water uses being recorded.

On July 14, under order of the Pennsylvania Public Utility Commission, mandatory controls on use of water were instituted. However, commercial car washing, lawn watering, and private car washing without the use of a hose were permitted. Consumption was reduced almost immediately by 20 percent. By July 22, with conditions worsening, further restrictions in water use were instituted. These restrictions ended car washing (commercial and private), use of water-cooled air conditioning, filling of swimming pools, and serving water in restaurants. These further conservation measures produced little in terms of reductions in water use. The water company advertised the following suggested ways of conserving water in the home:

1. Use only the smallest amount of water needed for tub baths.
2. Take quick showers.
3. Do not let water run for hand washing.
4. Use a cup or glass of water when brushing teeth.
5. Wash only full washer loads.
6. Wash dishes only once a day.
7. Flush toilets less frequently.
8. Check plumbing fixtures for leaks.
9. Serve drinking water only when requested.

As the public became more aware of the seriousness of the situation, use was cut by another 20 percent.

By August 17, the water company was forced to begin to obtain water from two quarries in the area. In addition, the company began trucking in water in 60 vehicles around the clock, increasing from 1 to 4.2 million gallons a day. By the time the rains came on September 14 ending the drought, more than 67 million gallons of water had been transported by truck. Furthermore, prior to the breaking of the drought, contingency plans had been laid, including laying emergency pipelines to other sources. One of those considered would have been a 16- to 20-inch pipe, which was laid some 16 miles to the Susquehanna River. Other plans included consideration of using railroad cars to bring water into the community.

Water Resources Engineers, Inc. (1972) undertook the task of determining economic losses that were incurred by the residential, industrial, commercial, and municipal sectors of the area served by the York Water Company. Results were obtained by a survey of residential and industrial water users and are summarized below.

Residential consumers include those billed on a *flat rate* and *metered* basis. Questionnaires were sent to approximately 40 percent of the flat-rate customers and 90 percent of the metered customers. Approximately 13 percent of the flat-rate customers and 20 percent of the metered customers returned completed questionnaires. The results of the survey summarizing losses suffered in dollar amounts are given in Table 5.1. Respondents further indicated that their priority for voluntary conservation in saving water during time of drought was as follows:

1. Lawn sprinkling.
2. Car washing.
3. Tub or shower.
4. Laundry.
5. Toilets.
6. Dishwashing.

Residential consumers further complained about the inconvenience experienced, taste and odor problems encountered, and concern over health hazards. Bottled water was consumed for drinking in large quantities here also.

Industrial consumers were surveyed by the Manufacturers' Association of York in October 1966 following the drought. Industrial consumers subdivided their estimated shortage costs in the following categories:

1. Drilling of wells.
2. Labor and materials.
3. Engineering services.
4. Shutdown of testing facilities using water.
5. Water treatment.
6. Miscellaneous.

The costs in each of these categories are summarized in Table 5.2. A summary of the estimated total industrial losses as a function of the percent reduction in water availability is shown in Figure 5.4.

Further visits with plant personnel familiar with activities during the 1966 drought provided a list of emergency measures undertaken by the companies to cope with shortage problems. The most common ones are summarized below:

1. A general request to all employees to conserve water throughout the plant.
2. Digging of wells on plant property.

3. Tapping of nearby creeks, ponds, and quarries.
4. Hauling water by tank truck.
5. Installation of water recirculation facilities and equipment.
6. Postponing strictly nonproductive operations such as research and testing that used significant amounts of water.

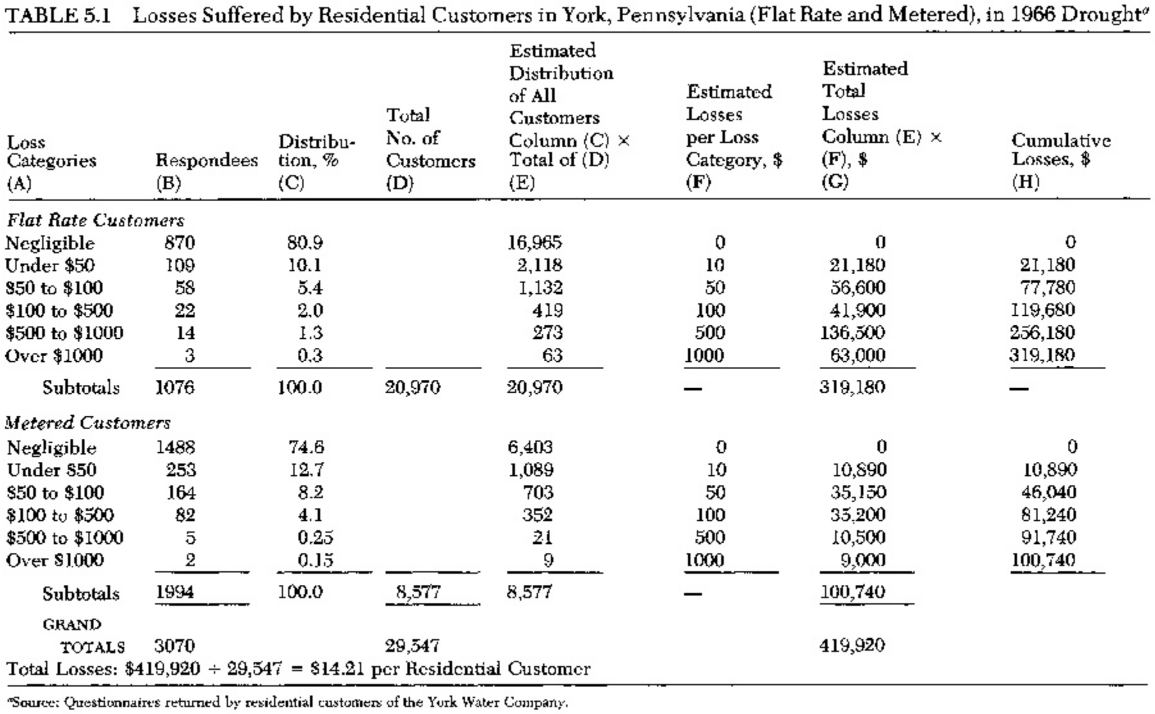

TABLE 5.1 Losses Suffered by Residential Customers in York, Pennsylvania (Flat Rate and Metered), in 1966 Drought[a]

Loss Categories (A)	Respondees (B)	Distribution, % (C)	Total No. of Customers (D)	Estimated Distribution of All Customers Column (C) × Total of (D) (E)	Estimated Losses per Loss Category, $ (F)	Estimated Total Losses Column (E) × (F), $ (G)	Cumulative Losses, $ (H)
Flat Rate Customers							
Negligible	870	80.9		16,965	0	0	0
Under $50	109	10.1		2,118	10	21,180	21,180
$50 to $100	58	5.4		1,132	50	56,600	77,780
$100 to $500	22	2.0		419	100	41,900	119,680
$500 to $1000	14	1.3		273	500	136,500	256,180
Over $1000	3	0.3		63	1000	63,000	319,180
Subtotals	1076	100.0	20,970	20,970	—	319,180	—
Metered Customers							
Negligible	1488	74.6		6,403	0	0	0
Under $50	253	12.7		1,089	10	10,890	10,890
$50 to $100	164	8.2		703	50	35,150	46,040
$100 to $500	82	4.1		352	100	35,200	81,240
$500 to $1000	5	0.25		21	500	10,500	91,740
Over $1000	2	0.15		9	1000	9,000	100,740
Subtotals	1994	100.0	8,577	8,577	—	100,740	
GRAND TOTALS	3070		29,547			419,920	

Total Losses: $419,920 ÷ 29,547 = $14.21 per Residential Customer

[a]Source: Questionnaires returned by residential customers of the York Water Company.

TABLE 5.2 Expenses for Emergency Services and Supplies Incurred by Large Water-Consuming Firms in the York, Pennsylvania, Area during 1966 Water Shortage Period[a]

Services and Supplies	4 Firms Locally Owned	21 Firms Externally Owned	Total of 25 Firms
Well drilling	$ 9,000	$ 21,772	$ 30,772
Processing changes to conserve water	13,000	38,833	51,833
Engineering services	5,000	18,678	23,678
Losses resulting from stopping of testing facilities requiring water	—	14,500	14,500
Supplementary water treatment	1,000	6,051	7,051
Other expenses	7,500	4,555	12,055
TOTALS	$35,500	$104,389	$139,889

[a]Source: Survey of the Manufacturers' Association of York, Pennsylvania.

Interviews with persons in commercial establishments failed to produce significant loss information. Commercial establishments such as car washes and nurseries indicated experiencing losses. One car wash drilled a well that provided water supply. Others had water trucked in to continue operation. One nursery experienced a loss of $30,000 when its stock was lost because of the ban on sprinkling.

No significant losses were experienced in the municipal sector. However, because water companies are often public utilities, the losses experienced by the York Water Company are indicative of the types of losses that can be experienced by public water utilities. Expenses incurred by the York Water Company for emergency water are summarized in Table 5.3. In addition to these increased expenses, the York Water Company suffered significant losses due to decreased revenues as water use dropped.

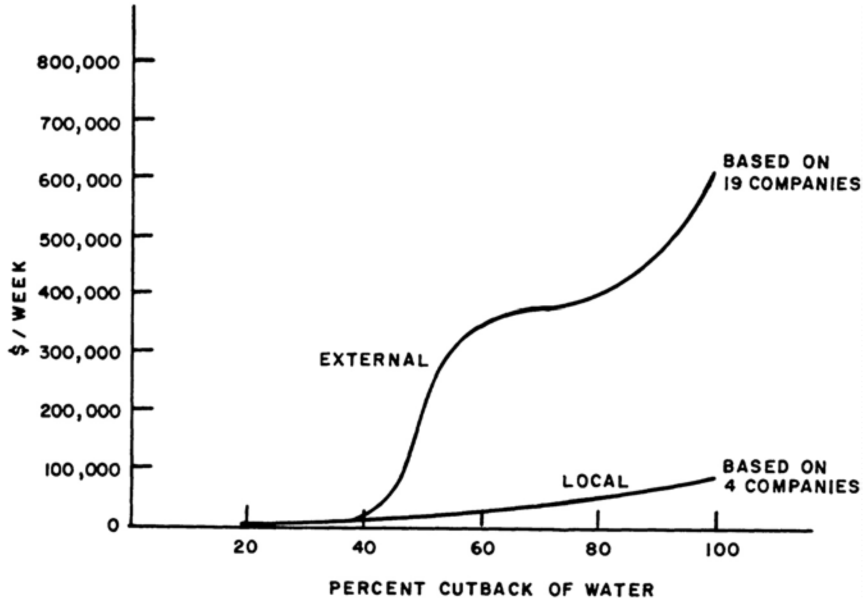

FIGURE 5.4 Industrial losses.

TRENTON, NEW JERSEY

A water shortage struck Trenton, New Jersey, in September 1975, which illustrates several factors common to water emergency situations (Cyphers, 1976; *The Evening Times,* 1975). The shortage was caused by failure in the pumping plant in the city's waterworks. Briefly, a check valve failed to operate as pumps were being stopped and new pumps started causing backflow from the city's storage reservoir leading to rupture of a culvert and the eventual flooding and incapacitation of the plant.

The damage occurred on Sunday, August 31. However, it was Friday, September 5, before water really began flowing again into the reservoirs and mains, leaving the city virtually without water for several days—the period Wednesday through Friday.

TABLE 5.3 Expenses for Emergency Water Incurred by the York Water Company, 1966a

	Paid to Firms		
	Locally Owned	Externally Owned	Total
Quarries	$ 40,475	$ 1,427	$ 41,902
Trucking	386,327	4,220	390,547
Railroad	1,703	5,388	7,091
Pipeline	600	7,504	8,104
West Branch	45,955	1,507	47,462
Other	23,628	21,189	44,817
TOTALS	$498,688	$41,235	$539,923

[a] Source: Records of the York Water Company.

A water emergency such as this—a distribution emergency—can hit a city at any time. Although volunteers by hundreds came from the city and suburbs to man auxiliary pumps and hastily strung fire hose and temporary pipe interconnections to neighboring water supplies, a serious crisis gripped the city. Once the plant was submerged, the crisis could not have been averted. However, the crisis strongly indicated the need for

1. A specific plan for water management action in the event of a crisis.
2. Consideration of regional interconnection of water supplies in urban areas to provide help in the event of crises.
3. Problems associated with repressurizing a water-supply system.

Agencies are actively considering action plans to permit coping with water-supply emergencies (Water Resources Engineers, Inc., 1975). The action of water managers has been shown to be an important variable in successfully dealing with a water crisis (Century Research Corporation, 1972; Young *et al.*, 1972). In Trenton, the water works management did not appear to estimate adequately the length of time pump repairs would take to complete. Thus, the public was not forewarned to conserve the dwindling water supply nor were measures to close industries or other water-consuming units made until water pressures began to fall in outlying areas.

The public did not realize the seriousness of the crisis until water pressure began to fall within the system. The lack of water pressure presents real safety problems to the city in such areas as ability to fight major fires. Furthermore, contamination of water supply and damage to water systems can occur as pressure falls and infiltration into water lines occurs. More than a day was required to repressurize the Trenton water system after repairs had been made, and users were warned to leave taps open to bleed air from the water lines and disinfect lines through superchlorination. In addition, residents were warned to boil all water before drinking for two days after the system was repressurized.

Hasty interconnections were made with neighboring cities by firemen and other volunteers using fire pumpers and civil defense pumps along with fire hose and other temporary piping. Some cities reportedly pumped so much water into the Trenton system that pumping had to be interrupted to keep from endangering their own supplies. Although these interconnections were most helpful, it was not possible to meet even the reduced needs of Trenton by using them. It is interesting to note that, although interconnection of electric power grids is an accepted practice, direct interconnection of water-supply systems is uncommon and even rare. This is due in part to the fact that water systems have storage as an integral part of them. Water-supply systems are often indirectly interconnected in that the same river or aquifer system may furnish water supplies for several cities. Direct interconnection and interchange of water by municipalities, political subdivisions, and water companies may be important safety features to be considered in water-systems design.

Teamwork by public officials, firemen, civil defense authorities, and private citizens developed quickly to keep the water crisis in Trenton from becoming much worse than in fact it became. Cooperation among the citizenry resulted in sharply reduced demand for water and major efforts to bring auxiliary water supplies from neighboring areas into use. Faster action on the part of public officials in recognizing the developing crisis coupled with an action plan for dealing with the shortage emergency would have helped the city stretch available supplies and cope with the crisis more effectively. As a distribution emergency can strike almost any city at any time, alert officials and contingency planning appear to be most necessary.

DELAWARE RIVER BASIN

A major drought struck the entire northeastern United Staes in the 1960's. A serious water shortage resulted in the Delaware River Basin and caused competition between several major cities and states for the limited available water (Hogerty, 1970). This water shortage illustrates the complex legal and institutional problems resulting when water crises precipitate confrontations between parties sharing water resources. Furthermore, this crisis clearly demonstrates the need for institutional mechanisms to mediate conflicting claims for limited water during shortage periods.

The Delaware River provides water to approximately 22 million people and a major portion of this country's industry. The river originates in New York State and forms part of the border for the states of Pennsylvania, New Jersey, and Delaware. Because of the vast number of people served by the Delaware and the number of major cities and states vying for its use, the river has had more than its share of water problems and political battles fought over it. It is certainly not surprising that during a period of drought the Delaware would become a source of controversy. When the drought of the 1960's struck the northeastern United States, New York City depended on the Delaware River for one third of its water requirements. Philadelphia met approximately one half of its water-supply requirements from the Delaware River, which at New Jersey supplied portions of the requirements for a number of cities including Trenton and New Brunswick. For many years, attempts to effect regional management of Delaware water resources had been tried. After efforts to develop an interstate compact failed in the 1920's, litigation among New York City, New Jersey, and Pennyslvania led to a 1931 ruling of the U.S. Supreme Court permitting New York City to divert water from the upper Delaware even though the New York City metropolitan area did not lie within the basin.

Joint legislation in the affected states led to the creation of the Interstate Commission on the Delaware in 1936, which was superseded in 1961 by the Delaware River Basin Commission (DRBC). The DRBC had powers to administer and manage the use of the Delaware water and possessed regulatory authority as well. The Commission had the power to carry out a 1954 decree of the U.S. Supreme Court regulating releases and diversions within the basin.

The years before 1961 proved to be ones of water abundance, and officials estimated adequate water supplies in the Delaware River Basin to meet water requirements until the year 2010. However, during the period 1962–1966, a serious drought began, which would last approximately 4 years and would be more serious than any to hit the Northeast since at least 1820. During the period 1961–1965, the precipitation deficiency equaled one full year of average rainfall.

The effects of this drought were felt throughout the basin at different times. Portions of New Jersey began to feel the effects of the drought in 1964 and met the challenge by encouraging conservation measures. By 1965, a drought emergency was declared by the Governor of New Jersey.

New York City, which possesses the world's largest municipal water works, felt the effects of the drought in 1964 with reservoir storage being reduced to levels causing concern to public officials. However, these officials were interested in not alarming the citizens. Thus, assurances were given through early 1965 that there appeared to be no real cause for alarm. By April 1965, water levels in storage reservoirs were at such dangerous levels that stringent restrictions were placed in effect to conserve dwindling reserves. Prohibition against outside uses such as lawn sprinkling, washing automobiles, and flushing walks were begun in an effort to avert uses not considered absolutely necessary.

Trouble spots in Pennsylvania in 1965 were confined largely to tributary streams in which spring-fed systems were beginning to run out of water. Philadelphia was not experiencing difficulties but was concerned with the intrusion of salt water into the Delaware as river flows began declining.

By mid-June 1965, four years after the drought had begun, the City of New York, fearing a major water emergency as reservoir levels declined, abruptly stopped making its downstream releases from its upper Delaware reservoirs as required by Interstate Compact and Supreme Court decree. The Delaware River Master was unable to get New York to honor his order to begin making required releases again.

The situation continued to worsen as the States of New York, New Jersey, and Pennsylvania considered alternative action to protect their dwindling water supplies. Although the DRBC had emergency powers that could be invoked to supersede compact provisions and make emergency water allocations, some doubted that the agency could be effective in a dispute between states.

A meeting of the DRBC was called in early July. At this meeting, plans were proposed by the parties to the crisis and by the DRBC staff. A subsequent meeting was held, and, after much negotiation and analytical investigation, the DRBC declared an emergency and adopted two resolutions defining a set of reservoir releases and diversion rates, which were accepted by the parties as a compromise solution. A continuing set of agreements resulting from studies of latest hydrologic data served as an evolving compromise solution to the water emergency being experienced.

The DRBC and the involved states sought and received federal assistance in the form of disaster relief and agency aid. The crisis also served as leverage to secure passage of the Federal Water Resources Planning Act. The drought lasted until the spring of 1967, with DRBC continuing to allocate scarce water resources. The Commission successfully served to settle differences between the parties to the DRBC compact when a drought emergency struck. The Commission staff was able to evaluate technical features of solution alternatives and obtain compromise agreements to serve each of the affected parties. The DRBC had successfully survived the emergency and demonstrated the ability of river basin commissions to meet the needs of several states comprising its membership.

SUMMARY AND CONCLUSIONS

Water-supply systems are designed to meet man's need for one of the most basic resources—water. Considering a need so basic, one would expect that a great deal of information would be available regarding the social and economic effects of deficits in water supply upon residential, commercial, and industrial consumers. Surprisingly, this is not the case. Thus, water-resource planners and systems designers have only fragmentary information concerning the nature of water-use characteristics and effects of shortages when developing their designs.

People can and do reduce water usage rather sigificantly in response to emergencies or deficits in supply. Thus, it might appear that designing water-supply systems presuming that all desires for water will be met at all times may be unrealistic, unusually costly, and unnecessary. Irrigation systems in the arid Southwest are often designed including a probability of shortage.

Research is needed to define water-use characteristics leading to a greater understanding of the range of alternatives open to governmental planners and water agencies and companies in designing water-supply systems and promoting effective use of water resources. Some research has been undertaken to identify water requirements and water-use characteristics (Century Research Corporation, 1972; Potter *et al.,* 1976; Water Resources Engineers, Inc., 1975; Young *et al.,* 1972; Lofting and Davis, Chapter 3). However, the amount of research completed to date is limited compared with that needed to support water planners and systems designers as they forecast water needs and plan systems to supply these needs.

Some of the types of research needed are as follows:

1. Audits of experience in areas that have been subjected to water shortage, particularly over extended periods of time.
2. Identification of water requirements for various uses within homes, commercial establishments, and industrial plants, classifying these uses according to quantity used and economic and demographic differences.
3. Development of quantitative measures of effects of varying degrees of water deficits on water users, considering ranges of frequency, duration, and magnitude of shortage and variation of economic and demographic conditions.
4. Consideration of the feasibility of interconnecting water-supply systems providing for transfer of water particularly where different sources of supply are present.
5. Study of the effects of alternative institutional arrangements making possible cooperative action between cities, water companies, states, and other political divisions.
6. Evaluation to alternative contingency plans in various localities or water systems in different classifications to select managerial actions appropriate in the face of water emergencies.
7. Investigation of the economic and social effects of short- and long-term variations in water supply upon residential, commercial, and industrial users.

Research in these and related areas is fundamental to the successful design of water-supply systems. At a time when water utility budgets are coming under increasing pressure, this research is greatly needed.

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III WATER-RESOURCE DESIGN AND PRACTICE

6

Water-Resource Systems Planning

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INTRODUCTION

Given the stochastic nature of streamflow, the planning, design, and operation of water-resource systems are necessarily subject to uncertainty. This is particularly so when dealing with design criteria that incorporate extrema. The future inflows to which the system is meant to respond are unknown and not predictable with a reasonable degree of reliability. Nonetheless, stochastic models of streamflow may be constructed and used to assess the risks associated with alternative system designs.[1] Basically, this entails the construction of stochastic flow models not for predictive purposes but to generate many sequences of synthetic flows such that each sequence may be regarded as being an equally likely realization of future sets of flows. With the set of synthetic flow sequences, a better assessment may be made (usually by simulation) of the expected performance of a system design than with the historical flows alone.[2,3]

A variety of synthetic flow-generating models has been developed, and although they differ in their construct, they are all based on the assumption that streamflow is a stationary process so that the values of the models' parameters are time invariant. The assumption of stationarity may be questioned, particularly in a region where land use has changed and the water resources have undergone development. Apart from economic activities, the assumption of stationarity may be questioned in terms of climatic change. Recent climatic literature has pointed out that the past several decades have been a period of rather mild and stable climate but that the future may be less so. If this is indeed true, then more severe floods and droughts may be expected in the relatively near future. Whether or not the climate is changing is subject to debate concerning the time scale over which change is defined; if it is changing, the nature of the change and how and when it would impact on hydrology are uncertain.

If climatic changes are reflected in a decrease in precipitation or prolongation of drought periods, then water-supply systems in years ahead may be stressed. The uncertainties as to the nature and magnitude of climatic changes and of consequent impacts on water resources compound the problems of uncertainty associated with the planning, design, and operation of water-resource systems. Although it may not be possible at present quantitatively to define climatic change and its hydrologic impacts even in probabilistic terms, the uncertainty can be dealt with explicitly in the development and management of water-resource systems. The manner in which this might be done is discussed below.

We introduce the concepts of robustness and resilience; these terms, which originated in statistics[4] and ecology,[5,6] have not heretofore been used in a water-resource context. Several definitions are proposed, but no definitive version is reached. The proposals are not inconsistent or contradictory—they emphasize different aspects of the concepts.

CLIMATIC CHANGE

Climatic change may be realized in a number of different ways.[7,8] If climate is regarded as a stochastic process, then change would be manifest in the parameters of the probability distributions and in the specification of the appropriate density function of such variables as temperature and precipitation. In addition, change may be reflected in the measures of climatic persistence or the extent to which climatic events in one time period are related to those in another. The difficulty in measuring climatic change is due largely to the fact that a definition of change, at least an operational definition, is yet to be widely accepted. Change implies a trend, real or apparent. Classical statistical literature has pointed out the pitfalls in detecting trends in short historical records. Even if climate is a stationary process from the long-run point of view, a climatic anomaly is, from an operational perspective, a change if the anomaly persists over the economic planning horizon. While the long-run nature of climate is of major scientific interest, immediate interest in water-resources planning lies in the short run, say 50 to 100 years.

It is difficult to discern trends from historical records of temperature and precipitation, particularly as the records are short as measured against geologic time and the quality of the records may have been affected by changes in the location of stations and by natural or man-induced changes in ambient conditions. Statistical analysis of trends in climate are based not so much on historical records as on a variety of long-term surrogate measures of climate such as tree rings, mud varves, and evidences of glacial advances and retreats, as well as historical accounts of past climatic events. The appeal of tree-ring records is their continuity and length spanning several centuries. The records are relatively easy to obtain on a wide geographical basis.

The tendency for tree-ring widths to decrease in absolute value and to become less variable with time is ascribed to the mechanics of growth and is essentially removed by transforming a nonstationary sequence of ring widths into a stationary sequence of ring indices.[9] The oscillatory character of sequences of tree-ring indices is ascribed to temporal changes in precipitation excesses and deficiencies. Much has been done in reconstructing estimates of past climates from tree-ring indices, but less effort has been given to the reconstruction of streamflows. In the absence of causal tree growth–streamflow models, regression of streamflows on tree-ring indices is a basis of flow reconstruction.

Regression, however, may disturb the statistical properties of the reconstructed flows relative to the historical flows. Tree-ring indices are more normally distributed and more highly autocorrelated than streamflow. These properties of tree-ring indices are passed to (and embedded in) the reconstructed flows, and, in addition, regression renders the reconstructed flows less variable than the historic ones unless random components are introduced specifically to preserve higher moments. The differences in the statistical properties between reconstructed and historical flows may not be attributed entirely to regression; the manner in which tree-ring widths are transformed into indices may also contribute. Whether the differences in statistical properties are sufficient to offset the utility of the reconstructed flows in planning and management of water-resource systems remains to be determined.

Apart from a few efforts to reconstruct flow sequences on the basis of tree-ring and other geochronologic records, hydrologic modeling has been concerned mainly with short-range forecasting of runoff events rather than predicting long-run hydrologic impacts of climatic changes. Thus, at present, there is little in the hydrologic literature to guide water-resource planners and managers as to the effects of climatic changes.

From the climatic literature, it is possible to construct a number of climatic scenarios that might be regarded as realizable in the near future, say, over the economic time horizon for project design. Among the scenarios might be one of increased variability of precipitation, one of declining temperatures, and others of a more complex nature. Although alternative scenarios can be constructed, it is unlikely that climatologists would be willing to assign probabilities to them. Their reluctance to do so is not without reason. The causal arguments favoring any one scenario are not strong. Moreover, models for making reliable long-range predictions of climate do not exist, and the prospects do not appear to be good for making reliable short-range, say weekly or monthly, meteorological forecasts. Meteorological variability generally is accommodated by flexible operating rules for reservoir systems; this is not a primary concern of this chapter. But the various statistical studies supporting climatic trends cannot be discounted in planning water-resource systems without first evaluating their economic and operational consequences.

A climatic scenario is not easily mapped into a water-resource scenario, except perhaps in a gross descriptive way. Changes in temperature and precipitation regimes cause changes in cloud cover and radiation transfer that can initiate shifts in patterns of human settlement and development. Changes in streamflow patterns cause further geomorphological changes and are themselves affected by the extent to which regional flora and fauna become adapted to new climatic regimes.

Among hydrologic phenomena, it is the extremes—the floods and minimal flows—that exert the greatest stress and exact the greatest penalties on the area's economy. Perhaps a small decrease in temperature could result in heavier snowpacks and delay in melting, thus altering the timing of snowmelt floods and perhaps increasing the magnitude of the floods if melting is delayed until heavy rains occur. Changes in the timing and magnitude of floods would impact the operation of reservoirs for flood control, hydropower, or water supply. If climatic change is in the form of longer periods of rainfall deficiency relative to long-term regional averages, then droughts measured in terms of low flows may be intensified in terms of both flow deficiencies and their duration. Severe droughts (as measured by intensity or duration) may in some cases overtax existing water-supply systems.

Large systems typically have substantial redundancy and robustness that enable them technologically and institutionally to adapt to large stresses. Recent studies of the northeast drought,[10] 1961–1965, show the remarkable extent of short-run adaptation by the community to phenomena that could, in fact, be manifestations of an undetected climatic shift. If hydrologic consequences of questionable origin persist, institutional measures (insurance, subsidies, zoning, for example) are available as an alternative to precipitous and irreversible structural measures (reservoirs, pipelines, well fields, for example). To assess fully the consequences of climatic shifts, the tradeoffs among these measures must be evaluated and articulated.

The exact way in which complex changes in climate would impact on water resources has not been addressed; and until research along these lines is undertaken, there is no way analytically to map a climatic scenario into its water-resource consequence. And even if this could be done, the probability of realization within the economic time horizon of the water-resource scenario would be conditioned on that of the climatic one, the latter probability still to be defined.

WATER-RESOURCE SYSTEM DESIGN

A long streamflow record, the basis for design of most water-resource systems, constitutes fragile information in that it represents a combination of deterministic and stochastic elements whose fluctuations cannot readily be associated with climatic shifts. However strong might be the evidence that climate is changing or that its population parameters are different than heretofore, the noise in the “black boxes” that map climate into flow are so large that it may be extremely difficult to detect climatic shifts by examining hydrologic data alone, and it might therefore be still more difficult to modify existing systems or specify new designs on the basis of climatic change.

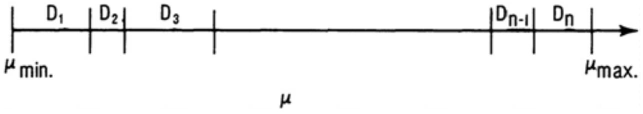

FIGURE 6.1 Optimal system design conditioned on ranges of μ.

The difficulties noted above are elaborated here. It is assumed initially that design of the water-resource system at hand can be optimized on the basis of a single parameter, namely, the population mean of annual streamflow at some gauging location. It is further assumed that the design decision (in however many dimensions or variables, such as the types and sizes of projects and their appurtenant structures, their sequencing, and their operation) is divided into a number of discrete design choices designated D_1, D_2, . . . , D_n, so that for any value of the population mean μ there is a unique design Di that optimizes the system objective function. This is shown in Figure 6.1, for which the line μ-space is divided into segments through which design D_i is optimal. Of course, the value of μ is never available. Nonetheless, our construct is based on the reduction in performance attributed to less than perfect information, so that it is appropriate to assume here that D_i is conditioned upon μ.

Some designs are more robust than others in that they are applicable over a wider range of μ-values, while some are optimal for narrow ranges cf the population mean. This is the most elementary definition; maximal robustness would be associated with some D_i optimal for all values of μ. Bayes's theorem provides another approach11 to the robustness of a particular design D_i:

Pr (D_i is chosen) · Pr (Di is optimal | D_i is chosen)

= Pr (D_i is optimal · Pr (D_i is chosen | D_i is optimal).

Both products are the joint probability that D_i is chosen *and* is optimal. The robustness could be given by either conditional probability, but both have shortcomings. Pr (*Di* is optimal | D_i is chosen) could be very close to unity if D_i is in fact optimal whenever chosen, however infrequently; Pr (D_i is chosen | D_i is optimal) could also be close to unity if D_i is chosen whenever it is optimal, however infrequently. The former conditional probability is a measure of robustness of the *system,* the latter a measure of robustness of the *design process.* Economic issues introduced later clarify the distinction.

Consider the loss of information attached to estimating the mean μ, for the case in which design depends only on estimates of that parameter. Suppose only two designs are available, D_1 and D_2, and that the associated ranges of μ are as shown in Figure 6.2. No other values of μ can be obtained. Because of the loss of information inherent in the sampling (information) program, $\bar{x}$ (the sample mean) is not a perfect estimator of μ. The figure shows that a wide range of $\bar{x}$-values could, at probability level p, be attached to populations characterized by ranges $\mu_1 \leq \mu \leq \mu_2$ and $\mu_2 \leq \mu \leq \mu_3$, respectively.* The divergence associated with each "funnel" is measured by the efficacy of the sampling program; the funnels need not be identical or symmetrical. Clearly D_1 should be chosen for $\bar{x}_1 \leq \bar{x} \leq \bar{x}_2$ and D_2 for $\bar{x}_3 \leq \bar{x} \leq \bar{x}_4$; the range $\bar{x}_2 < \bar{x} < \bar{x}_3$ provides some difficulties, and we discuss below how the concept of regret can help to choose between D_1 and D_2. This choice, which depends on economics, is importantly different from the mathematical choice between ranges of μ.

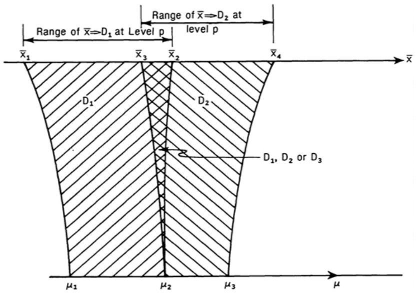

FIGURE 6.2 Impact of information loss on choice of system design.

Another possibility is that we identify a new design alternative D_3, to be chosen whenever the sample mean $\bar{x}$ falls in the double-hatched interior funnel. D_3 would never be optimal if μ were known; hence the funnel converges to a point on the μ-axis. In the discussion that follows, it should be noted that such designs, which are promoted to optimality only because of the uncertainty in estimating μ, can be among the finite set of design choices subject to analysis. Another approach to defining robustness at probability level of design D_1 is given by the ratio $(\bar{x}_2 - \bar{x}_1)/(\bar{x}_3 - \bar{x}_1)$, and that of D_2 by $(\bar{x}_4 - \bar{x}_3)/(\bar{x}_4 - \bar{x}_2)$, while the p-level robustness of the system is $[(\bar{x}_2 - \bar{x}_1) + (\bar{x}_4 - \bar{x}_3)]/(\bar{x}_4 - \bar{x}_1)$. The geometric interpretations are evident from Figure 6.2

The above concept can be generalized to encompass the mean, μ, and the standard deviation, σ, of the annual flows. Figures 3(a) and 3(b) show how the several designs D_i carve the decision space in the (μ,σ)-plane. The plane might be divided into a number of discrete zones, each associated with a design D_i [Figure 3(a)], or there might be smooth contourlike loci [Figure 3(b)] that define combinations along which design D_i should be chosen. The important questions are the extent to which information about the parameters' impacts on economic and institutional issues and the consequent likelihood that a new design choice would be required to meet system performance criteria under those new parameter values.

In traditional water-resource design methodologies there is uncertainty as to the mean flow, more uncertainty about the standard deviation, and even more uncertainty about the higher moments of the flow probability density functions. But if examination of Figures 3(a) and 3(b) indicates that the same design D_i (or some slight modification thereof) would serve over an area of the (μ,σ)-plane attached to some climatic scenario, precise specification of those parameter values becomes unimportant in the design of the water-resource system. In other words, if design D_i is optimal within a particular sector of the (μ,σ)-plane, and if there is confidence that current and modified parameter values lie within that sector even

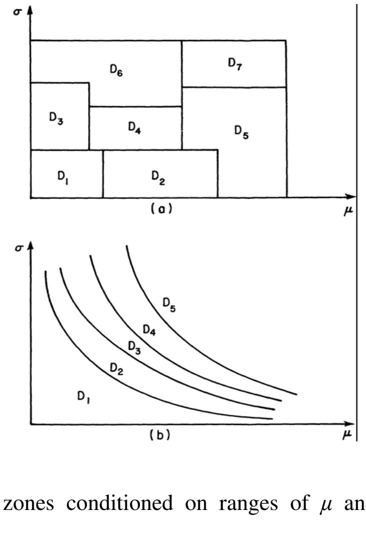

FIGURE 6.3 (a) Optimal system design zones conditioned on ranges of μ and σ. (b) Optimal system design loci conditioned on ranges of μ and σ.

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*The set (x_1,x_3) is the union of all the probability intervals for each μ in the interval $[\mu_1,\mu_2]$. Therefore for any μ subject to μ_2, then with probability p or greater, $\bar{x}_1 \leq \bar{x}\,\bar{x}_2$.

though they cannot be specified exactly, then nothing would be gained by collecting more information or even by identifying whether changes in the population moments are due to climatic shifts, oscillations, cycles, or other forms of nonstationarity.

Generalization to the third and higher moments is conceptually trivial but numerically subtle. If the decision space is augmented by a third dimension, say, the coefficient of skewness, γ, and the autocorrelation of order k, ρk, then the space may be carved into disjoint segments, each of which may be warped and to each of which is attached a design choice D_i. Experience in design of water-resource systems suggests that robustness and orientation of design contours or segments are strongly related to system objectives. For example, if the system priority is to serve agricultural and water-supply purposes, the design is likely to depend primarily on the lower moments or measures of central tendency of the flow probability distribution, and the design will tend to be stable or robust along the axes of the higher moments. Put another way, if one is designing on the basis of the mean flow alone, even modest storage facilities will generally remove enough variability from the tails of the flow probability distribution to render the optimal design relatively insensitive to skewness, γ. It thus becomes less important to identify closely the population skewness, to mount the necessary gauging program that would define it more precisely, or to be concerned over whether γ has been affected by climatic changes.

On the other hand, if the system is designed against extrema, more extensive information about γ and the higher moments might be indicated because the design choice would then be expected to be more sensitive to the value of γ. This would be manifest in Figure 3(b) by more closely spaced contours.[12,13]

It becomes more difficult when we move from flow parameters and ask instead about the effect of climatic changes on water-resource system designs. These changes are manifest as (filtered) changes in precipitation and temperature patterns, which must be filtered or mapped into apparent or potential changes in flow regime, which, in turn, dictate potential changes in system design. Thus potential shifts in the climatic parameters must be mapped through two filters before their effects on design choices can be evaluated. And, unfortunately, the filters are very noisy. Because of the complex delaying phenomena that are part of the hydrologic cycle and that are expressed in runoff and storage relations, we can only imprecisely map climatic shifts into changes in flow patterns (and even less well can we impute or detect climatic changes from flow changes).

Even if there were to be a verifiable change in precipitation, say, a small increase in the mean annual value, it is not clear that the increment would be reflected in flow measurements over the short run coincident with the economic planning horizon. Typically, there would be a change in vegetative cover so that only some of the incremental precipitation would appear as incremental runoff, the rest being diverted to modified interception and evapotranspiration. Changes in temperature, whether due to changes in precipitation or to independent causes, might occur; these might produce further shifts in the vegetative cover or in land-use patterns (which might result from changes in cropping patterns induced by small changes in the thermal regime). In any case, however induced, changes in cropping patterns and land use imply new runoff coefficients for the region, so that with limited hydrometeorologic data the incremental precipitation cannot reliably be mapped directly into incremental flow. The same unreliability governs for decreases in mean precipitation.

It is interesting to consider the rate at which regions adapt to new climatologic characteristics. The evolution of new vegetative patterns, the development of residential or commercial properties, and other long-term adjustments such as geomorphologic changes do not occur instantaneously. Adaptation to new precipitation patterns can be presumed to occur at about the same rate manifest by the precipitation, so it might be quite difficult to detect significant changes in runoff moments due to changes in precipitation and temperature.

Traditional descriptive hydrology is that branch of the subject that converts fundamental processes (precipitation and temperature) into flows and their moments, where estimates of the moments may be subject to large sampling errors.[14,15] Early efforts to study transfer of hydrologic information made little reference to economic criteria but were based mainly on maximization of hydrologic information.[16 –20] Stochastic hydrology is that branch of the discipline that converts statistical parameters of flows into designs or into an array of technologically feasible design choices, which, upon economic analysis, lead ultimately to a final choice. Both conversions add statistical noise to the signals generated by previous analyses. Part of the design problem is to identify the types of climatic shift that might be anticipated and to determine if they are sufficiently precipitous with respect to flow characteristics to dictate a change in system design. It is not necessary for this purpose to know or to try to determine whether there *is* a true climatic shift. This may be an interesting scientific question, important in its own right, but it is virtually meaningless for the design of water-resource systems. It is also unimportant to know if the population moments of the flow distribution are modified, because, again, while this might be an important hydrologic matter, it is important for water-resource design if, and only if, the changes, when coupled with economic criteria, lead to a new design.

Let D_i be the design that optimally meets the system objective given the ith combination of values of flow parameters. There are n different designs available, corresponding to the subspaces into which the flow parameter space, say (μ, σ, γ), is divided and, possibly, the zones of overlap in the sample space. These are ignored for the moment. The problem of continuous decisions is not treated here. One outcome of the Paretian analysis de scribed at the end of this chapter is a small set of design options that form the basis of further negotiation. Thus there is strong precedent for using a discrete number of design choices. D_i is the optimal design corresponding to a particular point in the (μ, σ, γ)-space. D_1* is the design actually chosen when the designer perceives the sample estimates of the population parameters to be those of the *i*th combination. This may not require that the sample estimates themselves lie in the ranges spanned by $(\mu, \sigma, \gamma)_i$. For example, as shown in Figure 6.2, the range of $\bar{x}$ that leads to D_1 is not congruent to that for μ, and similarly for D_2. If the designer could always identify correctly the population parameters, the design problem would be trivial and the correct decision would always be made. But the mapping from sample parameters to design contains opportunities for overlap and error. Thus the use of mathematical surfaces to separate the several decision options should be modified to accommodate zones of ambiguity, a complication dealt with later.

It is assumed that the designer always makes the correct decision based on the available climatic evidence; that is, design rules lead unambiguously from estimates $(\bar{x}, s, g)_i$ to design D_i. Suppose there are only two designs or decisions available: to build (D_1) or not to build (D_2) the system. The parameter space for flows is divided into two segments: that segment for which the structure should be built (S_1, climatic shift) and that for which it should not be built (S_2, no climatic shift). The designer cannot observe S_i directly but makes measurements, trend analyses, projections, and other climatic studies from which the evidence indicates (but not with certainty) that state S_1 or state S_2 governs. The two sets of climatic evidence are E_1 for state S_1 and E_2 for state S_2, and while the evidence can lead to a wrong decision, it can never lead to "no decision." If evidence E_i is obtained, then state S_i is assumed to govern and decision D_i* is made. The decision D_i* is optimal if the evidence E_i points to the correct state S_i, and non-optimal otherwise. Let evidence E_i be available so design D_1* is made. If the evidence is correct and state S_i obtains, then the decision is correct and the optimal design is D_1. Conversely, if the evidence leads to an incorrect assessment of the system state, the choice is D_1* (to build), whereas the optimal design should be D_2 (not to build). Analysis of the uncertainty can be compressed into a few compact statements concerning the conditional probabilities that relate the availability of evidence E_i and the occurrence of states S_i. The tighter the relationship between climatic and flow variables, the more likely it is that the correct flow description and design are extracted from climatic evidence.

A mathematical formalism handles some of the statistical issues. Again resorting to Bayes's theorem, the joint probability that evidence E_i and state S_i occur jointly is given by

$$\Pr(E_i, S_i) = \Pr(E_i \mid S_i)\Pr(S_i) = \Pr(S_i \mid E_i)$$

It is interesting to consider "the probability of making the right decision" and to tie this to another candidate definition of robustness. $\Pr(E_i \mid S_i)$ is the conditional probability that the evidence points to state S_i given that S_i governs; the sum $\sum_i \Pr(E_i \mid S_i)$ is the probability of a correct outcome because D_i is selected for S_i. $\Pr(S_i \mid E_i)$ is the probability that state S_i obtains given the evidence E_i; the sum $\sum_i \Pr(S_i \mid E_i)$, is the probability of a correct decision D_i. Robustness cannot be deduced from these probabilities alone, or in summation, because these values do not include the notion of a nonoptimal design performing "reasonably well" under different conditions *Sj.* If the evidence is an unbiased estimator of the states so that the marginal densities of *S* and *E* are identical, the conditional probabilities are equal.

The notion that the probability densities of E_i and S_i are equal does not imply that E_i is a good (in some sense) indicator of S_i. It merely states that E_i is observed as often as S_i, but it may happen that E_i is observed when S_j, some other state, obtains. In other words, the joint or simultaneous occurrence of E_i *and* S_i may be rare even though $\Pr(E_i) = \Pr(S_i)$. The essence of the conditional occurrence is contained in what are known as matrices of conditional probability, which may be written as $\Pr(E_i \mid S_i)$ or $\Pr(S_i \mid E_i)$, depending on the conditioned variable. These cannot be deduced from each other unless more information, in the form of the marginal or unconditioned probabilities $\Pr(E_i)$ and $\Pr(S_i)$, or the joint density $\Pr(E_i, S_i)$, is available. The probabilities are arrayed in a square matrix whose elements are the conditional probabilities that states S_1 and S_2 will be realized given that evidence E_1 is available. The row sums are unity because one or the other state must occur. If the marginal probabilities of S_i and E_i are unequal, it is important to determine whether the design objective is to maximize the probability of a good outcome. A technique for dealing with this issue is the decision-theoretic concept known as *regret* (see Matrix 1).

Suppose three discrete designs are available, that each corresponds to a set of population moments, and that net benefits can be arrayed in a matrix whose elements represent net benefits (however calculated and discounted)

Matrix 1 E, S—Marginal Probability Matrix

	State		
Evi-dence	S_1	S_2	
E_1	$\Pr(S_1 \mid E_1)$	$\Pr(S_2 \mid E_1)$	1
E_2	$\Pr(S_1 \mid E_2)$	$\Pr(S_2 \mid E_2)$	1

associated with selection of design D_i* when design D_j would have been optimal (see Matrix 2). There is no design reserved for the case in which it is impossible to discriminate among population moments (as in Figure 6.2, where D_3 was optional in the range of overlap but not elsewhere). Elements along the main diagonal are maximal for their columns because the optimal design (by definition) returns net benefits that are larger than those that would accrue to any other decision. It does not follow that elements along the main diagonal are the largest elements in their rows.

Matrix 2 Net Benefit Matrix

	Optimal Design		
Actual Design	D_1	D_2	D_3
D_1*	11	8	2
D_2*	6	9	4
D_3*	10	5	12

If each element in a column is subtracted from the maximal value in that column, the difference is a measure of the opportunity loss or regret associated with having made decision D_i* when D_j would have been optimal. (See Matrix 3.)

There are several criteria for extracting a decision from the regret matrix. One particularly conservative objective is to minimize the maximal regret. The maximal value in any row of the regret matrix identifies the worst benefit situation that can occur if a particular decision is made; a conservative design technique would be to minimize over all the row maxima by selecting that row for which the maximal regret is smallest.

Matrix 3 Regret Matrix

	Optimal Design		
Actual Design	D_1	D_2	D_3
D_1*	0	1	10
D_2*	5	0	8
D_3*	10	5	12

Other objectives can be used, including minimizing the expected regret. The probabilities required to estimate the expected regret are derived from Bayesian analysis, perhaps incorporating subjective probabilities, whereupon it is straightforward to identify an optimal decision.

It is also reasonable to use regret analysis to identify the expected gain associated with improving our ability to make correct estimates of the system state (climate). In other words, it might happen that an investment in information transfer or data collection would increase the diagonal elements of the *E, S* marginal probability matrix, implying thereby a higher probability that the climate state S_i will be realized when climatic evidence E_i is available. The result of the increase would be smaller probabilities associated with off-diagonal elements in the regret matrix, whose result in turn would be smaller expected losses associated with the decisions D_i* (see Matrix 4), and the regret matrix would be as shown in Matrix 5.

Matrix 4 Net Benefit Matrix

	Optimal Design		
Actual Design	D_1	D_2	D_3
D_1*	11	8	2
D_2*	6	9	4
D_3*	10	5	12
D_4*	6	6	6

Clearly D_3* minimizes expected regret for a uniform prior distribution attached to the states. Equally clear is the fact that under no realized state S_i does D_4* maximize net benefits. Its value lies in its robustness—in the insensitivity of its performance to the true optimal selection. D_4* would never be chosen if S_i were known; it can be interpreted as a "hedge" in real problems, for which E_i is known but no unique S_i is unambiguously indicated. Another candidate that naturally presents itself as a measure of robustness of design D_i is σ_i^{-1}, where σ_i is the standard deviation of the elements in row *i* of the regret matrix. Robustness by itself does not imply a good design.

The mean and standard deviation of the rows of the regret matrix in this example are (3.7, 4.5), (4.3, 3.3), (1.7, 1.9), and (4.7, 1.2). In the final section we deal with how to choose among such combinations of expectation and standard deviation.

Matrix 5 Regret Matrix

	Optimal Design		
Actual Design	D_1	D_2	D_3
D_1*	0	1	10
D_2*	5	0	8
D_3*	1	4	0
D_4*	5	3	6

THE 3 R'S: ROBUSTNESS, REGRET, AND RESILIENCE

The above sections introduce the concepts of robustness, regret, and resilience. These concepts are important, even in the absence of climatic concerns, and therefore merit further elaboration.

Robustness refers to the insensitivity of system design to errors, random or otherwise, in the estimates of those parameters affecting design choice. For example, suppose the design of a water-resource system is dependent only on the mean, μ, and the standard deviation, σ, of the annual inflows to the system. The optimal design associated with μ and σ is denoted D_i. The design D_i is said to be robust *at probability level p* if sample estimates of μ and σ lead to the choice of D_i with probability p. There is no meaning attached to robustness without an associated probability level. A geometric representation of robustness is as follows.

Let $(\mu,\sigma)\rightarrow D_i$ denote the set of all pairs of values of μ and σ for which the optimal system design is D_i. This set is shown as a footprint Ai on the (μ,σ)-population plane in Figure 6.4. The range of sample values $\bar{x}$ and s associated with a given (population) point in the set, perhaps derived from a particular climatic scenario, are unknown, but they may be estimated from available hydrometeorologic data. The ranges of the estimates, $\bar{x}$ and s, about μ and σ, are shown on the $(\bar{x},s)$-sample plane in Figure 6.4. All sample values $(\bar{x},s)$ bounded by probability p yield the set D_i' of designs, presumed to be optimal for the sample estimates $(\bar{x},s)$.

The level of information is functionally related to the sample size, the assumed population model, the probability contour or p-level, the estimating techniques, and the values of μ and σ.[12,13,20] For all points $(\mu, \sigma) \rightarrow D_i$, the (probability) p-envelope of all $(\bar{x},s) \rightarrow D_i'$ is delineated on the $(\bar{x},s)$-sample plane and projected downward onto the (μ, σ)-population plane. This projection is not merely a vertical transfer of the envelope. The design mechanism or algorithm, the operating policy, the number of potential design decisions, and other factors dictate the nature of the reflection back to the (μ, σ)-plane. The robustness of design D_i can be measured by the ratio A_i to A_i', where A_i denotes the area containing D_i on the (μ, σ)-population plane and A_i' denotes the area on the (μ, σ)-population plane contained with the projected p-envelope. In general, the area A_i is contained within A_i'; if not, the desired ratio is of that portion of A contained within A' to A_i'. Robustness is at a maximum, $A_i/A_i' = 1$, if, as illustrated in Figure 6.5, the sample estimates are perfect ($\bar{x} = \mu$ and $s = \sigma$), in which case D_i' D_i. It would be instructive to attach a probabilistic interpretation to the robustness ratio A_i/A_i', but none is readily available. If all the points within the p-level envelope in the $(\bar{x}, s)$ or (μ, σ) planes were equally likely, the ratio would approximate the conditional probability $\Pr(D_i \text{ is chosen} \mid D_i \text{ is optimal})$, thus showing the equivalence of the analytical and graphical interpretations of robustness.

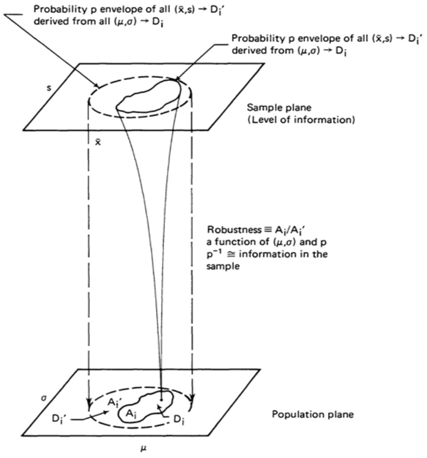

FIGURE 6.4 Robustness of system design given imperfect information.

Further the robustness could be evaluated by simulation as follows:

1. Identify all feasible designs D_i, $i = 1, 2 \ldots, n$.
2. Pick a $(\mu, \sigma, \gamma, \ldots)$ point and the associated optimal design D_i.
3. Generate a long trace of flows, which are then grouped into many replications with each characterized by sample estimates $(\bar{x}, s, g, \ldots)_i$.
4. Each replication yields a design. If the design is the optimal design D_i, score a success; otherwise, score a failure.
5. Calculate directly the conditional probabilities associated with design ror, noting that iconid=psigma Pr(D_i is optimal | D_i is chosen) is a measure of robustness of the system design while $\sum_i$ Pr(D_i is chosen | D_i is optimal) is a measure of robustness for the design process.

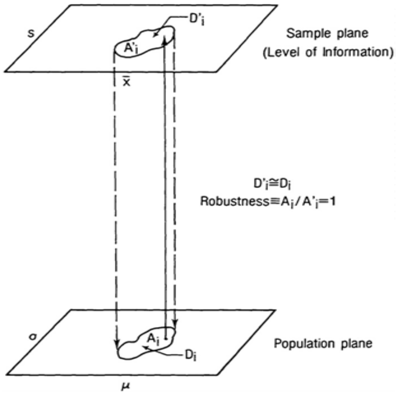

FIGURE 6.5 Robustness of system design given perfect information.

If the available information yields a design belonging to the set D_i' when in fact the optimal design is D_j, then there is a resulting opportunity loss, referred to as regret, which is measured by the intersection of the surface $(\mu, \sigma) \to D_j$ and the surface $(\bar{x}, s) \to D_i'$, as shown in Figures 6.6 and 6.7. With perfect information, Di′ ` D_i, in which case $(\mu, \sigma) \to D_j$ and $(\bar{x}, s) \to D_i'$ are disjoint, so there is no regret.

The system D_i, if it has the built-in buffering and redundancy typical of large water-resource systems, can be operated technically and institutionally to simulate another system D_j such that the resulting economic losses would be small and bounded by some fraction, say α percent. This capability is referred to as *resilience* at level α. Geometrically resilience is depicted in Figure 6.8 by the extension of the $(\mu, \sigma) \to D_i$ surface. The ratio of the area contained within the extended surface to the area

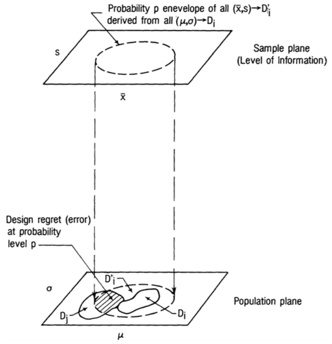

FIGURE 6.6 Regret in system design.

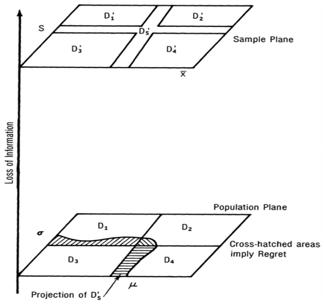

FIGURE 6.7 Regret in system design.

contained within the projected *p*-envelope is the measure of resilience.*

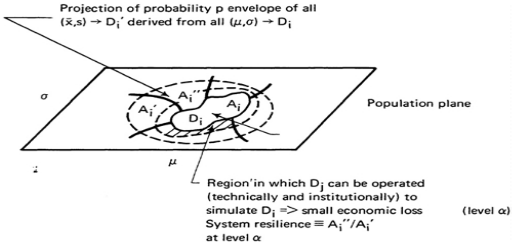

FIGURE 6.8 System resilience.

If the argument for, say, D_i is extended to cover all D_i, perhaps weighted by the *a priori* probabilities for each D_i, then the sum of weighted resilience measures is a measure of *system* resilience. Extensions of this argument lead to conclusions that many small reservoirs may for a significant range of cost functions somehow be "better" than a single large reservoir and that the economic cost of losing the economies of scale is equivalent to an insurance premium that purchases *resilience.* For example, if husband and wife elect to travel in two separate airplanes, they lose economies of scale leg, family plan fares, taxicabs, etc. but gain resilience in that they drive essentially to zero the probability that their children will be orphaned!

Another way to draw the distinctions between robustness of system design and robustness of system outcome is to note the role of sensitivity analysis in design of water-treatment facilities.† In one study, four plants were to be built over a number of years to meet growing demands. The least-cost solutions were identified, but 11 other solutions (any of which might have been reached by an experienced designer) lay within 3.3 percent of the minimal cost. Indeed, it would be reasonable to posit that the range of costs lies well within the noise that might be anticipated from the design algorithm. The outcome is thus insensitive to the decision; we say it is robust with respect to the solution.

However, if the economic parameters of the decision model are changed, Harrington shows how one solution remains optimal even though the value of the outcome changes significantly; this exemplifies sensitivity of the outcome with respect to model parameters and insensitivity (robustness) of the decision with respect to these same parameters.

CONFLICTS OF INTEREST IN WATER-RESOURCES PLANNING

Conflicts in system design are the rule rather than the exception. Typically, two or more parties dispute the algorithm for calculation of benefits, and the issue is resolved only after long and costly litigation. Courts of law are called upon to render judgments in areas for which they could hardly be less well equipped.

Another class of system-design objectives incorporates *a priori* assignment of probabilities to the several states S_i, the net effect of which is weighting the various regret elements and tipping the decision. This is a political and social reality, not necessarily immoral or unethical; it reflects the fact that the priority assessments of the decision maker inevitably align themselves more closely with those of one participant (in the decision-making process) than another. For most resource development programs, particularly those characterized by multiple-purpose use, it is virtually impossible to imagine that all the participants, all the vested economic and social interest groups, all the impacted public and private agencies will have the same perception of objectives, benefits, and costs for the system. Conflicting interests are the rule rather than the exception, and because the decisions must somehow be made, by someone or some agency, it is better to anticipate these interests than to be surprised by their occurrence and thus to be unprepared to deal with them in a systematic, disciplined, and rational way.[21]

Climatic shifts may not produce conflicts of interest, but they accentuate existing conflicts. Note that specification of the parameter *p* is important in design, and two agencies or conflicting parties may have different levels of risk aversion and hence may propose different "optimal designs." Somehow the conflict between agency constraints and objectives must be resolved. In some of the western states, conflicts between agricultural and energy interests are anticipated over the use of available water supplies. The conflicts might be aggravated by climatic shifts resulting in a decrease in water supplies. On the other hand, a farmer might be willing to relinquish some of his water rights if he were convinced that climatic shifts would lead to increased water availability or increased precipitation whereby dry-land farming would be profitable.

There are system objective functions that, when applied to the regret matrix, can be used to identify nondominated design alternatives for future negotiation and tradeoff. This is known as Paretian analysis. It emphasizes that many solutions are admissible in that they represent output combinations from which it is impossible to improve the position of one participant without worsening the position of at least one other. In other words, the participants agree that impoverishment of each other is not their objective (as it is in classical two-person, zero-sum games) but that each would be happy to have everyone else do well as long as this does not occur at his own expense. If one participant perceives that his inter

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*The use of ρ,α to define resilience is consistent with specification of confidence and tolerance limits in statistics. The concepts are identical,

†J. J. Harrington, personal communication.

ests are jeopardized by continued improvement in the position of another, he can threaten to terminate the negotiations or otherwise derail the decision-making process.

He could agree to a less desirable position if side payments were made. Our social and institutional structure is particularly weak in arranging for such side payments because they smack of bribery and extortion, but moral rectitude is not an inherent human trait so much as it is a social tradition, and we could improve our performance in this regard.

The implication is that we can derive from the analysis a set of potential solutions that are not dominated; each represents a point on the Paretian frontier.

Consider Figure 6.9, which shows the net benefits perceived by each of two participants in a decision-making process. In the general case, with more than two participants, the dimensionality of the decision space would exceed two. The coordinate axes represent the values assigned by the several participants (in this case, only 2) to each potential decision. All those designs that lie to the south and west of another design are *dominated* because both participants could improve their positions by moving to the north and east. As long as the move does not require that participant *X* move westward, or that participant *Y* move southward, the design is dominated. All nondominated designs are connected by an envelope along which tradeoffs or negotiations can take place. This envelope is called the Paretian frontier and contains all points that are Pareto-admissible. The solution will lie along that frontier; generally speaking, it will lie closer to the design preferred by that participant with the greatest political clout, the largest army, the most sheep or goats, the most money, or the most of whatever currency is recognized by the parties to negotiate. The final negotiated position may not accord with the objective function of any of the participants or of the administrative body responsible for implementing the decision. In this sense, Paretian analysis is different from traditional benefit/cost analysis, which imposes an objective function (by force of arms, legislation, or whatever) and proceeds to optimize the entire system, for all prospective users, on the basis of that imposed objective.

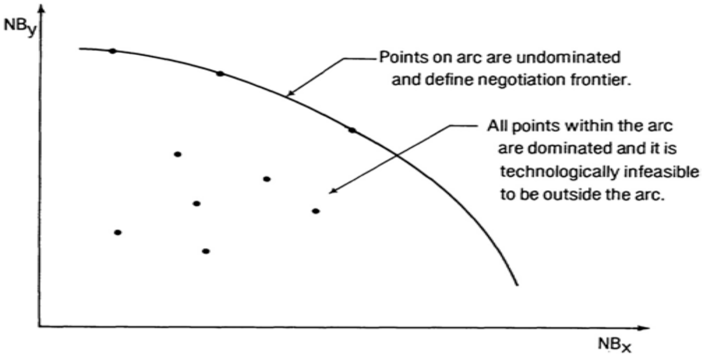

FIGURE 6.9 Pareto negotiation frontier.

Another kind of conflict involves the tradeoff between return and risk; all of us face and resolve such issues daily.[22,23] In terms of a reservoir design problem, it is appropriate to ask how expected (or some other measure of) net benefits should be combined with variation (say, the standard deviation) of regret to form a negotiation set. This is the matter of comparing the four outcomes calculated from the regret matrix developed earlier. Variation in regret (or net benefits) is undesirable so that the two axes of the Paretian analysis would be mean (abscissa) and deviation (ordinate) of benefits, and it would be advantageous to move to the southeast (maximize the mean, minimize the deviation) to define the Paretian negotiation frontier. The concept of dominance still governs; only the direction changes.

The means and standard deviations of net benefits for D_1 through D_4 are (6.0, 3.65), (6.0, 2.16), (8.5, 3.51), and (1.0, 0). On this evidence, D_1 is dominated by D_2, but no choice can be made among the three remaining candidates without explicit consideration of the tradeoffs, negotiations, and side payments. On the basis of expected regret, D_3 dominates all other solutions. If specific prior densities were assigned to the D_i (or S_i), other results would obtain.

The point here is that the decision-making process, or what we have also called the design process, is dependent to an important degree on political, institutional, economic, military, social, and other nontechnologic factors. To attempt to assess the effect of climate change, natural or man-made, without recourse to these non-technologic issues would be irresponsible.

CONCLUSIONS

This chapter does not resolve any issues by providing statistical tests and algorithms for adapting standard design rules to the case in which climatic shift is a potential perturbation on system design. Rather, it lays out a formalism for economic, institutional, and social adaptation to a variety of political perceptions on the value of hydrometeorologic information in reducing risk of error in anticipation of climatic shifts.

At the present state of the meteorologic and climatologic arts, it is not likely that more definitive conclusions can be reached. But it is comforting to recognize that most large systems contain so much buffering and redundancy that resilient design can be operationally achieved without recourse to sophisticated or elaborate projections about the climate. When not designing for extrema, the problem is more subtle, but the concept of regret could be applied through the system and testing of different climatic scenarios and of their effect on hydrologic regimes.

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7

Climatic Change and Water Supply: How Sensitive is the Northeast?

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INTRODUCTION

Water supply is an essential service that requires professional water managers to plan continuously and carefully as system expansion is costly and time-consuming. Reduced to its simplest terms, water-resources planning with its water-supply component is a search for the most cost-effective means of striking a balance between sets of estimated demand with sets of estimated supply. Further, however, water-supply plans must also take into consideration constraints imposed by the larger environment within which the water manager operates: limitations imposed by law, custom, institutions, fiscal capabilities, and long-time horizons appropriate to political decision-making. Indeed the time scales for the water-resources planner and the political system are dramatically out of synchronization. In most small jurisdictions, for example, the short-range future is tomorrow. Mid-range futures come before the next election, and long-range just beyond that election. Usually, only larger cities, regional jurisdictions, states, or the federal government can look at planning horizons of 20–50 years. In terms of local decision-making, what might occur in 100 years is almost entirely without significance.

In this context, the professional water manager's lot is not a happy one. His customers castigate him in the event of even short-term water shortages, while the academic community, particularly economists and environmentalists, accuse him of habitually overestimating demand and overbuilding facilities. Further, his operation and construction plans rest on uncertain estimates of demand based, in turn, on equally uncertain population and economic development projections. Even the range of variation in his supply is based on predictions made from historical data and statistical manipulations.

Hence, it is understandable that the introduction of yet another element of uncertainty—climatic change—leaves the water manager still more vulnerable to accusations that he did not correctly consider the unforeseeable in making his calculations. The water-resources planner needs better information to assess the importance of climatic change as a valid planning factor and its acceptability in the public decision-making process. The probability of climatic change could be considered a goad to action or additional fuel for the "let's wait and see" style of facilities planning.

THE REGIONAL SETTING

For more than 10 years, uncertainties about the validity of demand projections, fiscal and environmental constraints, and simple procrastination have stalled all major projects that would increase water supplies in the northeastern United States. In 1972, the North Atlantic Regional Water Resources Study (NAR) found that water-quality maintenance and water supply for public, industrial, and powerplant cooling purposes were the most important water-resource problems of the northeastern United States (NAS, 1972a). Intuitively, water supply is likely to be far more sensitive to climatic change than water quality maintenance, although the latter might also be adversely affected. Future water needs for additional municipal use based on today's experience were estimated to range from a low of 1400 million gallons per day (mgd) (61.3 m^3/sec) in 1980 to a high of 10,600 mgd (464 m^3/sec) in 2020 (NAR, 1972a). Even greater quantities have been estimated to be needed for industrial and power cooling.

The northeastern United States as defined in the NAR study encompasses all river basins within the United States draining into the Atlantic Ocean north from the Virginia–North Carolina border, the Lake Champlain drainage, and the St. Lawrence River drainage in the United States south of the junction of the St. Lawrence River and the international border. This land area of about 167,000 square miles (432,500 km^2) includes all or parts of 13 states and the District of Columbia. The region contains about 5 percent of the nation's land area, but it holds about 25 percent of its population and produces nearly 30 percent of its wealth (NAR, 1972a).

On the average, some 1200 water suppliers in the region presently furnish 5.5 billion gallons per day (bgd) (241 m^3/sec) and serve more than 47 million people or 88 percent of the area's total population. About 4.7 bgd (206 m^3/sec) is used in domestic supplies. The remainder serves industrial, commercial, and municipal purposes. About 76 percent of the water used in these supplies comes from surface waters, the remainder from groundwater. Depending on which projection of growth is realized, populations are likely to require 9.5 to 10.9 bgd (416 to 478m^3/sec) by the year 2000 and from 13.1 to 16.0 bgd (574 to 701 m^3/sec) by 2020. By far the major share of this water will come from surface sources with reservoirs as the major device for collecting supply (NAR, 1972b).

Average annual runoff from the region is 163 bgd (714 m^3/sec) 123 bgd (5389 m^3/sec) available 90 percent of the time (U.S. Water Resources Council, 1968). Seasonal variability, which is generally moderate, can be high in individual basins. Months of high flow are usually March and April, the lowest flow tending to occur in August and September. At the extreme end of the scale, at the height of the drought in the early 1960's, runoff in the affected area was from between 45 and 60 percent of normal. The total drought period lasted 51 months.

Despite the fact that average annual draft on the waters of the region is less than one third of the annual runoff that can be expected to occur 95 percent of the time, severe local shortages have occurred in the past and are likely to occur again in the future. Recurrence of a major drought, coupled with the projected increases in demand, would cause larger and more widespread disruptions than have been experienced in the region so far.

This possibility is extremely significant in light of the fact that three metropolitan areas, Washington, New York, and southeastern New England, account for more than 70 percent of the total present average public water supply now furnished in the northeastern United States. From the foregoing it is obvious that water supply is a problem of tremendous magnitude in the northeastern United States and that water supply for these metropolitan regions is of particular concern.

EVALUATION OF CLIMATIC CHANGE

There are two major ways in which climatic change affects water supply. One is the effect it may have on demands such as lawn irrigation or the use of showers. Second is the effect on water sources such as streamflows or groundwater recharge. Of these, the second is likely to be far more important to metropolitan water management in the Northeast. Therefore, this paper will deal predominantly with changes in water sources and within these restrictions with streamflow, the most common source of metropolitan water supplies here.

Four parameters, singly or in combination, could be used as indicators of climatic change. They are the first three moments of the distribution of streamflow and persistency and the tendency of dry years to follow dry years and wet to follow wet. Records of streamflow allow us, within the limits imposed by their shortness, to estimate these parameters if we assume some specific distribution function as properly descriptive of streamflow. Climatic change, as expressed in streamflow, can then be described as a significant change in one or more of these four parameters and maybe even in the distribution function. This last change, however, is unlikely to be detected in practical human time space; and, therefore, changes in the four parameters, mean, standard deviation, skew, and persistency, would suffice to characterize climatic change.

To evaluate the effect of climatic change on the water supply systems of the Northeast, the most effective approach would be to project the direction and magnitude of such change, to translate this into streamflow records, and then to use these records to analyze the response of the present and projected future major water-supply systems to forecast change. Unfortunately, this straightforward approach is not feasible. While the specter of major changes in climate has been held before the public for a long time and while serious scientists have long debated this problem, the result of the debate has not been very helpful for the solution of problems faced by water-resources planners and managers. The one conclusion available to practicing professionals is that changes in climate are likely. However, the magnitude and timing and even the sign of the changes are unknown.

Under the present state of climatic forecasting and our ability to translate climatic data into streamflow, such an approach is not feasible. Furthermore, the possibility to construct long-term hydrologic records from secondary sources appears limited in the Northeast, although a consistent 239-year record of precipitation and temperature has been produced by Landsberg *et al.* (1968). Unfortunately, the errors associated with converting precipitation into streamflow are much higher than rainfall–runoff modelers have led us to believe (Todin and Wallis, 1974). Thus other ways must be attempted to assess the sensitivity of northeastern water supply systems to climatic change.

Three possibilities appear feasible: (1) to review individual cases and, on the basis of their previous response to existing climatic anomalies and on the basis of questioning some of the water managers, speculate on the response to climatic change; (2) to select certain broad criteria of water systems and speculate on the effect climatic changes might have on each; and (3) to select a method of synthetic streamflow generation, use generated streamflow as a decoupled surrogate for climate, arbitrarily vary parameters, and observe the effect of these variations on the safe yield that could be developed from this streamflow record.

Within the space and time limitations of this paper, all three will be attempted.

EXAMPLES OF METROPOLITAN WATER-SUPPLY PROBLEMS

The *Washington Metropolitan Region* in Virginia, Maryland, and the District of Columbia covers about 2800 square miles (7242 km^2). With a population of about 2.4 million, it is the ninth largest metropolitan area in the United States. Population projections postulate a likely growth of this area to 5.2 million people by 2000 and 6.8 million by 2020. This population generates a water demand averaging 390 mgd (17 m^3/sec) on its water supply today and a demand of 720 mgd (31.5 m^3/sec) and 925 mgd (41.5 m^3/sec) projected for the years 2000 and 2020, respectively (Northeastern United States Water Supply Study, 1975).

The major share of the present water demand, about 60 percent, is supplied by the generally unregulated flow of the Potomac River. The remainder comes from reservoirs on the Patuxent and Occoquan Creek. The two latter rivers are almost fully developed, and the Potomac can, in its present unregulated stage, barely supply present summer peak demands. Plans for the future foresee a mixture of regulation of the Potomac, local reservoirs, interconnections of water-supply systems, emergency restrictions, use of water-saving devices in new construction, and reuse of water from the Potomac estuary and advanced waste-treatment plants (Northeastern United States Water Supply Study, 1975).

To date, the existing water-supply sources and the institutions managing them have generally been successful. Even during the droughts of the 1930's and 1960's, restrictions did not pass the minor nuisance levels. This situation will not continue, however. Growth to date has been sufficient to outstrip the safe yield of the region's water sources under drought conditions, and even the most optimistic believers in controlled growth cannot show that continued increases in demand, albeit smaller ones than officially estimated, are likely. Planners have predicted this situation for a long time, and expansion plans go back to the 1940's; yet the response has been greater on rhetoric than on action. Only the suburban systems have made many significant improvements in source development, and there has been none at all in the last 10 years.

While water planners blame the environmentalists and the environmentalists blame the pigheadedness and lack of imagination of the water engineers, the reasons are more fundamental. One is the diversity of objectives relating to the social and economic development of the region. The other is that the existing institutions are geared to deal with relatively short-term problems in a political climate that demands that decisions be made for clearly visible reasons to achieve immediate results. The water problem of the area is not obviously visible. It is a long-range problem and its possible solutions are based on uncertain assumptions in both the demand and water aspects—assumptions that are based on often unpopular political decisions such as growth control or on statistical distributions of natural events that may or may not be valid.

In the face of these difficulties in decision making on water-supply development in which steps leading toward stabilization of supply and increases in water reuse are taken extremely slowly and under constant opposition from one side or the other, it would be hard to imagine that the process could include, with some realism, estimates of climatic change that are even more uncertain, less understood, and further in the future than annual and monthly variability now used in water-planning studies.

The New York Metropolitan Area covers 9345 square miles (24,200 km^2) in the states of New Jersey, New York, and Connecticut. It includes not only New York City but a number of municipalities with populations exceeding 150,000 and several hundred smaller communities. The area is not only a population center but contains a large number of manufacturing plants and the nation's largest concentration of financial, trade, professional, and communication services. Population is now estimated at about 19 million and expected to reach nearly 24 million by 2000 and nearly 27 million by 2020. Water demands today average 2760 mgd (121 m^3/sec) and are expected to reach 4050 mgd (177 m^3/sec) and 5120 mgd (224 m^3/sec) in 2000 and 2020, respectively. New York City's water-supply system provides more than 65 percent of today's demand, but its share is expected to shrink to less than 60 percent by 2020 (Northeastern United States Water Supply Study, 1975).

The New York metropolitan area is at present supplied by a large number of water-supply systems. The system that serves the city is by far the largest. It draws its supplies from a series of reservoirs located in the Croton, Catskill, and Upper Delaware watersheds. Other systems within the area use the streams of north and central New Jersey and western Connecticut. Safe yield of many of these water-supply systems is today barely sufficient to meet demands. The drought of the 1960's required stringent emergency restrictions. No major new water sources have been developed since the drought, and a comparable period of low supply starting today would likely have even greater effects.

Studies of additional sources of water supply show that the most important source for the area would be the Hudson River either by high-flow skimming or reservoir development on one or more of its tributaries. The second regional source, particularly for the New Jersey portion, is the Delaware River, through the controversial Tocks Island project. Lesser sources are in the smaller streams of New Jersey and Connecticut and groundwater in New Jersey and on Long Island. Metering of the New York City supply is also considered as a method to reduce demand (Northeastern United States Water Supply Study, 1975).

Here again, acrimonious debates have taken the place of action. Arguments over the merits of the Tocks Island area as a park or as a reservoir have been decided in favor of park development, removing the Delaware River as an expansion source for the New York–New Jersey metropolitan area. Equally, reservoir development in the Adirondacks had been practically outlawed by action of New York's electorate. Water-supply interconnections in New Jersey, installed during the drought, have been disconnected. As a result, the region is more susceptible to shortages now, and its choices for the future have been significantly narrowed. Institutional arguments between the state of New York and New York City, the emotional issue of New York City metering, and the city's monetary problems further complicate the situation. A Hudson River high-flow skimming project coupled with metering in the city appears to have some chance to be implemented and to solve New York City and state of New York water problems 10 years hence. In New Jersey, there is as yet no plan.

Even with a Hudson source development, the region's water system would be sensitive to climatic changes that change the runoff regimen of the source streams. Three points make it so. First, the Delaware's delicate balance between upstream diversions to New York City and the downstream needs for municipal and industrial water supply and estuarine salinity control could be easily upset by a relatively small reduction in long-term average runoff or the occurrence of long droughts. This balance is codified by existing legal decisions and interstate agreements; climatic change would bring changes here too, as discussed in Chapter 4. Second, the amounts available from highflow skimming of the Hudson, with consideration of both salinity control and fish spawning and migration, depend on the time-flow distribution. Changes in that distribution through climatic change could upset yield estimates. Third, groundwater yield on Long Island is directly related to local rainfall. Consistent short falls, for example, would rapidly reduce aquifer yield or increase the danger of saltwater intrusion.

The southeastern New England Metropolitan area in Massachusetts and Rhode Island encompasses 357 municipalities with an estimated population of 6.5 million today. Population projections foresee a growth to 8.5 and 9.7 million for the years 2000 and 2020, respectively. Water demands in this area were 749 mgd (33 m^3/sec) in 1965, and these demands are projected to increase to 1519 mgd (66 m^3/sec) in 2000 and to 1893 mgd (83 m^3/sec) in the year 2020 (Northeastern United States Water Supply Study, 1975).

This area is served today by 369 public water systems with a combined safe yield of 970 mgd (42 m^3/sec). The Metropolitan District Commission (MDC) system serving Boston and 41 nearby communities is by far the largest. Its supplies are drawn from tributaries of the Connecticut and the Merrimack through the Quabbin, Wachusetts, and Sudbury reservoirs. Other supplies come from the basins of the Ipswich, North, Taunton, Pawtuxet, Blackstone, Thames, and Powcatuck Rivers. Impoundments in these basins are the usual source of the water supplies. Present demands are approximately equal to safe yield, although the demand in the MDC system exceeds its safe yield by almost 1 percent now. During the drought of the 1960's, reservoir levels in the MDC system were very low, and drought of a longer duration would have caused significant shortages. Other communities in the area resorted to emergency restrictions, some of quite stringent nature.

Ongoing planning includes additional diversion of water from the Connecticut Basin and the Merrimack Basin, either through high-flow skimming or reservoir development, as well as through new reservoirs in the other aforementioned streams in the area and groundwater development (Northeastern United States Water Supply Study, 1975).

The major problem here is that there is a different constituency for the source area—western Massachusetts—and for the user area—Boston. These constituencies are economically and socially divergent and see little need to accommodate each other. To this must be added the perception of the supply. The reservoirs are full right now, and the drought is forgotten. Climatic changes that would produce longer dry and wet periods would tend to inhibit development further, as little can be completed even during a 5- or 6-year drought, and 10 years or longer of normal or above normal supply would allow people to forget the lessons of the last drought completely.

In a discussion of the problems of water supply and climatic change with the Chief of the Water Divisions of the Metropolitan District Commission, that official remarked that long-term changes in climate reflected in the availability of water would increase or decrease the vulnerability of this supply system but would not change his basic problem. “We look ahead, but not necessarily act on that look” is the way he put it (Matera, 1976). A decrease in the mean annual yield would be in his opinion most detrimental to Boston's water supply. Increased persistency, longer periods of less flow, would be the next most damaging manifestation of climatic change.

EVALUATION OF METROPOLITAN WATER SUPPLIES

There is a set of attributes that appears common to all the examples of major water-supply problem areas that can be used to evaluate the effect of climate change. While these attributes are common to all, the importance of each varies from area to area. Nine such attributes are considered here. First, there are four that are related to the resource itself: yield from unregulated streamflow, yield from reservoirs, yield from ground water, and quality of raw water. The next two related to the effectiveness of water-supply works: overall systems reliability and effectiveness of regional interconnections. The last three involve the management of water supply: magnitude and control of demand, cost of operation, and pressure on the water-supply system to expand and its ability to respond to change.

These attributes of metropolitan water-supply systems can then be evaluated against the four parameters of climatic change mentioned in the previous section. An additional characteristic of climatic change should also be considered. This is the speed with which these changes become manifest. Reactions to such changes are likely to be considerably different if change manifests itself over the span of a few years or comes gradually over periods as long as 20, 50, or even 100 years.

A speculative effect matrix could be constructed showing the effects of the enumerated manifestations of climatic change on the nine attributes of water systems. Table 7.1 presents such a matrix.

A SIMULATION APPROACH

A third way to evaluate the possible significance of climatic changes would be through the use of synthetic hydrology. Using streamflow as a surrogate for climate, alternative hydrologic scenarios could be constructed to cover a wide range of possibilities, permitting an evaluation of system sensitivity to change.

There are two major problems to this approach. First, the relationship between climatic variations, the way climatologists see them, and streamflow is largely undefined. This is particularly true when a specific stream and location on that stream must be considered. The second problem is the selection of a generating algorithm. Several streamflow generation models exist, each having its partisans and detractors within the hydrologic community.

For the initial analysis of this paper, it was assumed that monthly streamflow adequately described the water resource and that its variations could be represented by a skewed logarithmic lag-one Markovian model. Such a model can be characterized by four parameters. These are mean, standard deviation, skew, and serial correlation coefficients. These parameters can be used to generate streamflow traces representing alternative futures. By varying these four parameters, we can simulate some of the effects of climatic change on systems response. A computer program developed by Leo R. Beard and the Hydrologic Engineering Center is available that allows generation of such alternative synthetic streamflow records using observed or modified statistics (U.S. Army Corps of Engineers, 1971).

Using the aforementioned mathematical model and computer program, alternative streamflow records were generated for the Potomac River at the Point of Rocks gauge, where the drainage area is 9651 square miles (24,996 km^2). Statistics were computed from the existing record. Records from 1895 to 1970 were used to compute the logarithmic mean, standard deviation, skew, and serial correlation coefficient for each month. These statistics were then used to generate a 1000-year record and eight alternative “climatically changed” 1000-year records. For each of the alternative records, one set of statistics was varied. Table 7.2 shows the assumptions used for each data generation and the highest and lowest 1-month, 6-month, and 54-month flows, as well as the long-term average.

As no estimates of likely climatic change were available, the variations in statistics were arbitrarily chosen. As can be seen from Table 7.1, variations in the standard deviation not only greatly increase the range of monthly flows, they also increased the mean flow. Changes in the mean generally shift the entire population of data, and increases in the serial correlation coefficients have relatively little influence. A change of the skew coefficient had a far greater effect on the one-month extremes than on the longer and more critical high- or low-flow periods, a result to be expected since monthly correlations of the generating algorithm were rather small.

The 1000-year synthetic records generated were processed through a computer program developed by the

TABLE 7.1 Speculative Impact Matrix of Climatic Change

	Parameters of Climatic Change				
Attributes of Water Supply Systems	A Decrease in Mean Streamflow	B Increase in Variance of Streamflow	C Increase in Skew of Streamflow	D Increase in Persistence of Streamflow	E Speed with which Change Occurs
1. Yield from unregulated streams	Some effects, but likely not very large except if change in mean is large or combined with other changes	Severe effects; however, generally short term	Significant effects because number of days of low flow increase relative to few very high flow periods	Significant effects more through duration of low flows than severity	Not applicable
2. Yield from reservoirs	Significant to severe effects particularly if reservoirs develop a high percentage of the average flow	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Significant to severe effects especially if reservoir long-term storage is limited	Not applicable
3. Yield from groundwater	Significant in the long run, especially if draft on aquifer is near average recharge	Little if any significance	Little if any significance	Effects severe and of long duration	Not applicable
4. Quality of raw water	Probably insignificant effects except where large reservoirs are drawn to very low levels	Generally no effects except possible increase in turbidity during high flows	Little if any significance	Little if any significance	Not applicable

5. System reliability	Some effects, other than effects accounted for under 1–4	Some reduction due to constant change in flows in addition to effects under 1–4	Little or none, other than effects under 1–4	Little or none, other than effects under 1–4	Sudden changes severely affect reliability, slow ones less or not at all
6. Effectiveness of inter-system and interbasin connections	No change	Increased effectiveness if variance increases	Little effect	Reduced efficiency of interconnections because long droughts are usually also widespread	No change
7. Magnitude and control of demand	No significant effect	No significant effect; often reoccurring short-term restrictions may reduce their effectiveness	No significant effect	No significant effect; emergency restrictions likely to become less effective over long droughts	Significant and visible effects, relatively fast changes could force major steps toward conservation and demand control
8. Cost of operation of water system	No significant effects except for additional construction that might eventually ensue to alleviate long-term shortages	Possible increase due to turbidity, increased pumping between systems if applicable; possible additional reservoir construction	No significant effects likely	No significant effects except search for new sources	No effects
9. Pressure on and ability of the water system to respond to change	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would not be affected by hydrologic event	Pressure for expansion would be created, but rapid return to normal may for some time inhibit expansion	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would not be affected by hydrologic event	Pressure for expansion would mount over time and increase likelihood of action; however, long high flow periods may inhibit development	Sudden or relatively near future changes could increase action; long-term changes (20 years+) even if known would likely be ignored by existing institutions

author for the NAR study and adapted for use here by Bruce Morris, a student at Clark University. This program subjects the flow of the river under study to varying levels of drafts while varying the amount of usable storage in the system from 0 to that amount needed to meet all drafts without a month of failure. The program tabulates for each combination of draft and storage the number of months in which the target draft could not be furnished, the number of shortage periods of various length, the highest and the average shortage, and other information.

TABLE 7.2 Alternative Streamflow Records for Potomac River at Point of Rocks

	Average Flow in Cubic Feet per Second						
	1-Month		6-Month		54-Month		Total Record
Basis for Record Generation	Highest	Lowest	Highest	Lowest	Highest	Lowest	
76-year historical record							
Actual record 1895–1970	68,359	706	26,225	943	12,171	6205	9061
1000-year simulated records							
Observed statistics	80,529	439	34,437	1132	13,528	5455	9076
Standard deviation increased 10%	112,808	273	36,728	866	15,871	5353	9428
Standard deviation increased 20%	128,932	192	42,514	761	17,214	5270	9813
Log mean decreased 10%	70,647	329	28,464	893	12,846	4896	8152
Log mean decreased 20%	43,104	284	25,306	789	11,412	4344	7339
Serial correlation coefficient increased 10%	75,762	358	32,136	936	14,449	5376	9073
Serial correlation coefficient increased 20%	75,786	358	31,901	882	14,636	5315	9073
Skew coefficient increased +0.5	167,855	736	51,001	1223	16,996	5356	9233
Skew coefficient increased −0.5	57,011	159	25,720	823	12,748	5579	8938

Relationships between draft, storage, percent chance of meeting demand, and the different assumptions of statistical variations were then analyzed. The result of this analysis was generally disappointing to those who believe that climatic change should radically alter the water-supply planning process. No clear picture of the susceptibility of large water-supply shortages attributable to a specific statistical parameter developed. For instance, if 95 percent assurance of supply is required, the Potomac in its present state can supply about 1400 cubic feet/sec (cfs) (938 mgd or 130 m^3/sec). With the most unfavorable alternative tested, the yield was 1100 cfs (737 mgd or 122 m^3/sec) or a reduction of about 20 percent. With the same unfavorable trace, the full 1400 cfs were assured 91 percent of the time. The trace that produced this change assumed a reduction of the log-mean by 20 percent. The other alternative traces have less influence on the yield of the free-flowing river. Figure 7.1 shows the plot between draft and percentage of time the draft requirements can be fulfilled.

Adding storage into the system complicates the analysis and makes it even less satisfactory. The number of points now available for analysis of the apparently most important relationship, that between storage, draft, and shortages, is small; and storage and shortages vary from run to run even with the same statistics because of the random component in the data generation. Therefore, plots can only be sketched by smoothing and with a resulting reduction in accuracy. There are strong indications, however, that major increases in standard deviation are as important as reductions in log-mean. There are further indications that sensitivity to changes in the streamflow trace increases with the degree of development and with a decrease in the level of acceptable risk. In other words, the increase in storage needed to compensate for alternative scenarios and to maintain a specific draft increases with the size of the draft and with a decrease in the acceptable shortage index.

The results of this analysis can be accepted only as very preliminary. Various phenomena observed, such as the changes in mean flows accompanying changes in standard deviations, need further analyses. Also, other generating algorithms, including non-Markovian models, should be studied. Work toward this end has been initiated by the author in cooperation with James Wallis and others.

CONCLUSION

What does all this mean to those who must plan and manage the water supply of the northeastern United States? Apparently it has no importance to them now. There is not yet sufficient knowledge of climatic change or its effect on water supply to suggest any rational change in public policy. If, in addition, we add in the uncertainty of the timing of possible climatic changes, then it becomes even more certain that current planning does not have to be concerned with climatic change. On balance, it is the more easily perceived uncertainties at hand that are the appropriate guides to policy-making. If this study has any relevance to ongoing water-supply planning, it might reinforce the need for flexibility in plans and argue for a more adequate safety margin in the development of water supplies.

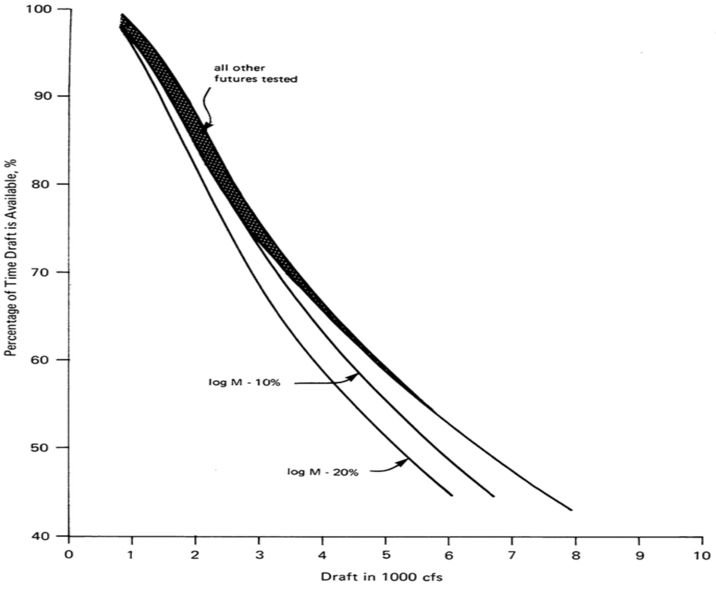

FIGURE 7.1 Potomac River at Point of Rocks. Draft-duration relationship without storage.

The conclusions of this chapter are as follows:

1. A full understanding of the possible relationships between climatic changes and water supply, its planning, and management is a desirable goal.
2. At minimum, a range of likely climatic-change scenarios should be available to the water-resources planner.
3. Much more detailed and complete analyses are required to assess the sensitivity of existing or projected water supplied to climatic variations. Such work should:

(a) Consider several streams throughout the region.
(b) Test different models for streamflow generation including those that preserve skewness directly without a logarithmic transformation and those that allow for greater long-term persistence than is possible with the Markov model used in this study.
(c) Postulate smaller increments between alternatives and make a far greater number of iterations for each alternative so that observed differences cannot be attributable to noise in the data.
(d) Use more detailed models of urban water-supply systems, including economic loss functions.

Beyond these preliminary results, it is appropriate to speculate on the changes in water-supply planning and decision-making occasioned by findings that significant climatic change is at hand or that such changes are of no consequence. In the latter case, unwarranted considerations should not be allowed to complicate and delay water supply plans and their implementation. If, however, significant climatic changes are likely, present planning methods must take them into account.

The most straightforward incorporation of information on climatic change would be the development of a series of water-resource projections analogous to Bureau of the Census population projections. These could be prepared on a national basis and then adapted to specific regional characteristics and uses. In this fashion, consistency could be maintained, while variations dictated by specific local circumstances could still be considered. Such alternative projections would complicate the hydrologic studies needed for water-supply planning and management, but the institutional decision process would not be significantly changed for near-term and midterm considerations. Should really large climatic changes appear likely for the more distant future, political decision-makers must be sensitized to deal with long-range planning futures and their associated increase in uncertainties.

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8

Impact on the Colorado River Basin and Southwest Water Supply

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INTRODUCTION

When the Spaniard Francisco de Ulloa first discovered the mouth of the Colorado River in 1537, a fierce tidal bore and river flow made him fearful for his ship (see Watkins *et al.*, 1969):

> We perceived the sea to run with so great a rage into the land that it was a thing much to be marvelled at; and with a fury it returned back again with the ebb . . . and some thought . . . that some great river might be the cause thereof.

De Ulloa sailed up the river delta as far as the confluence with the Gila. Today, Colorado River diversions have caused the river to disappear before reaching the Sea of Cortez. Therefore, such a journey is no longer a possibility.

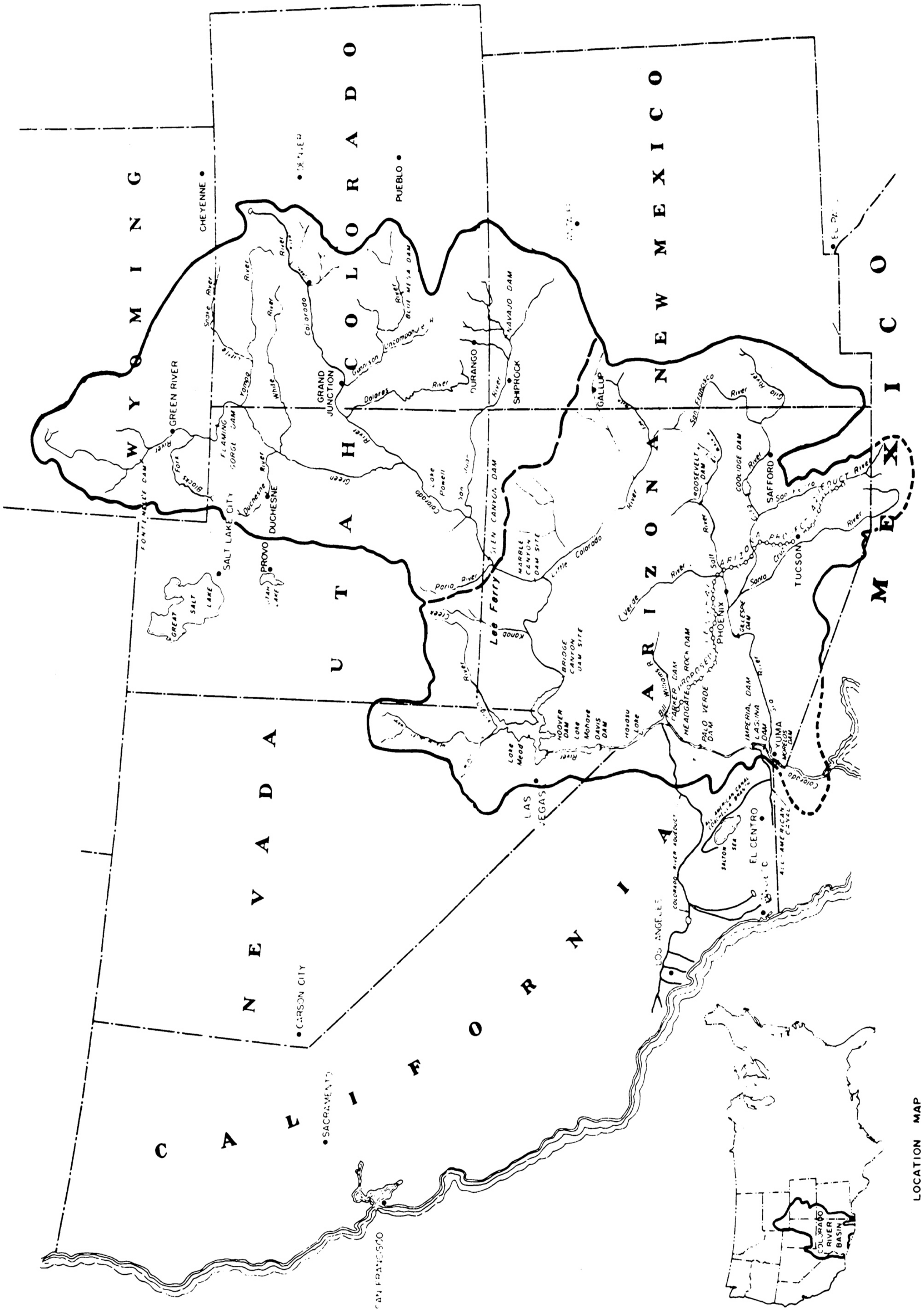
Considered here are the current and projected scenarios of one of the major river basins in the United States—the Colorado. Examined are the combined hydrologic, legal, and demand constraints and how these constraints are affected when accentuated by an additional adverse climatic future.

Thus, the problem to be considered in this paper is one of prediction, namely, the prediction of the effects of climatic variability and changes on future water supplies. The Colorado River Basin is presented as a case study. It is hoped that the estimates and predictions concluded here will strike the mark closer than those of J. C. Ives, an early explorer of the Southwest, who wrote:

> Ours has been the first, and will doubtless be the last party of whites to visit this profitless locality. It seems intended by nature that the Colorado River, along the greater portion of its lonely and majestic way, shall be forever unvisited and undisturbed.

The National Park Service reports that the forty-millionth visitor will enter Grand Canyon National Park sometime during the 1970's (Dolan *et al.,* 1974). Thus, we are confronted with an environmental impact of man on the river and an economic impact of the river on man.

The water resources of the southwest United States are dominated by the Colorado River Basin. This 243,000-square-mile basin can be thought to be analogous to a cat who has given birth to too many kittens—there just isn't enough “milk” to go around. With the exception of the


WYOMING
COLORADO
NEW MEXICO
UTAH
ARIZONA
NEVADA
CALIFORNIA
MEXICO
CHEYENNE
PUEBLO
GREEN RIVER
SALT LAKE CITY
PROVO
DUCHESNE
GRAND JUNCTION
DURANGO
SHIPROCK
GALLUP
LAS VEGAS
CARSON CITY
SACRAMENTO
SAN FRANCISCO
LOS ANGELES
EL CENTRO
YUMA
PHOENIX
TUCSON
SAFFORD
GREAT SALT LAKE
FONTENELLE DAM
FLAMING GORGE DAM
NAVAJO DAM
BLUE MESA DAM
GLEN CANYON DAM
Lake Powell
Lee Ferry
MARBLE CANYON DAM SITE
BRIDGE CANYON DAM SITE
HOOVER DAM
Lake Mead
Lake Mohave
DAVIS DAM
Lake Havasu
PARKER DAM
HEADGATE ROCK DAM
PALO VERDE DAM
IMPERIAL DAM
LAGUNA DAM
MORELOS DAM
ROOSEVELT DAM
COOLIDGE DAM
GILLESPIE DAM
SALTON SEA
ALL AMERICAN CANAL
COLORADO RIVER AQUEDUCT
CENTRAL ARIZONA PROJECT AQUEDUCT
Colorado River
Green River
Gunnison River
Dolores River
San Juan River
Little Colorado River
Gila River
Salt River
Verde River
Bill Williams River
Paria River
Kanab
San Francisco River
San Pedro River
Santa Cruz River
LOCATION MAP
COLORADO RIVER BASIN

deserts of the Great Basin, the Colorado River Basin has the greatest water deficiency (average precipitation less potential evapotranspiration) of any basin in the coterminous United States (Piper, 1965). Yet, more water is exported from the Colorado River Basin than from any other river basin in the United States (Committee on Water, 1968).

Any consideration of a negative climatic environment on the southwestern United States and particularly on the Colorado River Basin would immediately appear even to the most casual observer as a stress on a system already under considerable stress. It brings to mind A. A. Milne's lines from *Now We Are Six:*

At times like these the bravest knight

May find his armour much too tight.

Looking at the Colorado River system we find a highly variable and continuously modified hydrologic flow regime. The river is situated in a region whose need for water when projected 25 years into the future demonstrates that man's efforts of a half century ago to apportion the limited supply to the expected needs were inadequate to compensate for the vast difference between potential need and potential available supply.

GEOGRAPHIC DESCRIPTION

The 243,000-square-mile basin drainage involves areas in seven states and was arbitrarily divided by the Colorado River Compact at Lee Ferry, Arizona, into the Upper Colorado Basin and the Lower Colorado Basin for purposes of interstate administration.

The Upper Basin drainage includes those areas of Arizona, Colorado, New Mexico, Wyoming, and Utah that drain into the Colorado River above Lee Ferry, Arizona. It is bounded on the east and north by mountains forming the Continental Divide, and on the south it opens to the Lower Colorado region at Lee Ferry in northern Arizona.

The Colorado River rises in north-central Colorado in mountains more than 14,000 feet high. Then it travels 640 river miles through the Upper Basin to Lee Ferry at an elevation of 3000 feet. The major tributary is the Green River, which begins in Wyoming and discharges into the Colorado River in southeastern Utah, 730 miles from its origin and 220 river miles upstream from Lee Ferry.

The Lower Basin drainage includes most of Arizona, parts of southeastern Nevada, southeastern Utah, southeastern California, and western New Mexico (Figure 8.1).

A wide range of climate occurs because of differences in altitude, latitude, and topographic features. In the north, summers are short and warm, winters are long and cold. In the southern part, the summers are longer and the winters are moderate at low altitudes, but colder temperatures occur in the mountains.

From October to May, the precipitable moisture is transported by maritime air masses from the Pacific Ocean. During the summer months, most of the precipitation is brought from the Gulf of Mexico. A winter snowpack accumulates in the higher mountain regions and provides most of the surface runoff during the spring melting season.

The evaporation rates vary from approximately 30 inches in the northern, higher areas to approximately 86 inches in the southern part of the basin.

CURRENT LEGAL FRAMEWORK

The laws governing the Colorado River have been presented in detail by Meyers (1966) and Weatherford and Jacoby (1975). Only a brief summary of the major treaties, laws, and compacts will be presented here.

The allocation of the Colorado River is based on the concept of beneficial consumptive use. The allocation system operates at four levels: international, interregional, interstate, and intrastate (Weatherford and Jacoby, 1975).

The international allocation was accomplished by the Mexican Water Treaty of 1944. Mexico was guaranteed an annual amount of 1.5 million acre-feet (maf) except in times of extreme shortage. However, this treaty contained no provision for water quality. Thus, joint agreements in 1965 and 1973 called for a temporary agricultural drainage water bypass and eventually a desalting plant to improve the quality of water crossing the border.

The interregional allocation was achieved when Congress approved the Colorado River Compact, which became effective in June 1929. Sectional rivalry has caused the states included in the drainage basin to agree to an equal apportionment of the Colorado River waters between the states of the Upper Basin (composed of the states of Colorado, New Mexico, Utah, and Wyoming and a portion of Arizona) and the states of the Lower Basin (composed of the states of Arizona, California, and Nevada) [Colorado River Compact, 1922, Article III(b) and Article III(d)].

Traditionally, the fertile lowland valleys, i.e., the states of the Lower Division (Arizona, California, and Nevada), develop more rapidly than the mountainous headwater regions called the “areas of origin,” i.e., the states of the Upper Division (Colorado, New Mexico, Utah, and Wyoming). Thus the Upper Basin states insisted that an equitable apportionment of the river be made prior to the expenditure of large federal sums of money, which might result in a modification of equities adverse to the Upper Basin states. This is in essence what was achieved in the 1922 Colorado River Compact.

The intent of this landmark document was to give each basin the perpetual right to the “exclusive beneficial use of 7,500,000 acre-feet of water per annum. . . .” However, the Lower Basin was assured that depletion in the Upper Basin would allow at least a 75 maf flow to the Lower Basin at Lee Ferry in each successive ten-year period. Thus, the Lower Basin received a guaranteed ten-year, not annual, minimum flow, and the Upper Basin assumed the burden of any deficiency caused by a hydrologic dry cycle. However, there are differing viewpoints concerning this allocation. For example, Saunders (1976) states:

> The intent of the Colorado River Compact is clearly expressed in Article III(a) to make an equal division of water between the Upper and Lower Basins. Substantial analysis of the remainder of the Compact indicates this clear intent. Paragraph III(d) is not an apportionment at all, but an attempt to implement paragraph III(a) on the basis of a mutual mistake of facts as to how much water was available for apportionment. This being the case, the actual shortage of the water which has been discovered since the making of the Colorado River Compact must fall equally on the Upper and Lower Basins.

The allocation of the 1.5 maf to Mexico is also in disagreement. Holburt (1976) states that

> There is no agreement among the basin states of the interpretation of the Colorado River Compact with respect to the Mexican Water Treaty obligation of the Upper Basin states. The apparent position of representatives from the four Upper Basin states is that their obligation is zero. Representatives from the three Lower Basin states take the position that the obligation is 750,000 acre-feet a year plus losses, which could be as much as 150,000 af/yr, giving a total obligation of 900,000 acre-feet a year.

These differences have not yet been adjudicated because the development of water uses in the river has not yet brought the matter into sufficient focus to bring about a legal determination.

The interstate apportionment for the Lower Basin states was accomplished through the Boulder Canyon Project Act of 1928. Congress decided that a fair division of the first 7,500,000 acre-feet of the mainstream water would give 4,400,000 to California, 2,800,000 to Arizona, and 300,000 to Nevada; Arizona and California would each divide any surplus. The decree in *Arizona* v. *California* (1963) divides the surplus as Nevada, 4 percent; Arizona, 46 percent; and California, 50 percent.

The Upper Basin states reached agreement on a formula for further dividing their apportionment under the Colorado River Compact when they executed the Upper Colorado River Basin Compact. The Upper Colorado River Basin Compact of 1948 (1949) allots to Arizona 50,000 acre-feet per annum. The balance is apportioned to Colorado, 51.75 percent; New Mexico, 11.25 percent; Utah, 23.00 percent; and Wyoming, 14.00 percent.

Indian tribes were not parties to either the interregional allocation of the 1922 Compact or the interstate allocation of the 1948 Compact. Tribal water claims are based on the Winters Doctrine (*Winters* v. *United States,* 1908), which holds that the rights are not lost by nonuse but can persist indefinitely in an unquantified state. The reserved rights of five tribes in the Lower Basin have been adjudicated and quantified. The current maximum diversion quantity is 1 maf per annum. The consumptive use, which is a measure of the river depletion, is estimated to be approximately 615,000 acre-feet per year (Holburt, 1976).

It is anticipated that any further allocations to the Indian reservations will come out of the allocation of the state that contains the reservation.

The intrastate allocation is based on the doctrine of property ownership in water. This doctrine was developed to meet the needs of the area on a basis entirely foreign to the riparian doctrine of the English common law from which the United States derives its general system of law. The appropriation doctrine of the West is based on the proposition that whoever will invest the energy necessary to apply water of natural streams to beneficial use shall be protected in his right to use as against any later water developers. This right is limited to divert only what is needed for beneficial use. The title to the water is perpetually reserved in the people of the various states. This is subject to the right of the individual appropriator to take what he needs for beneficial use on the basis of “prior in time is prior in right.”

SURFACE-WATER RUNOFF

About 83 percent of the water that flows in the Colorado River Basin comes from the Upper Basin. The average annual precipitation throughout the entire Upper Basin is about 16 inches, which amounts to 93,440,000 acre-feet per year. Thus, approximately 15 percent runs off as most of the precipitation is lost to evapotranspiration in the Upper Basin.

One of the most famous and controversial hydrologic records in the United States is that of the virgin flow of the Colorado River at Lee Ferry, Colorado. Lee Ferry is defined as a point on the Colorado River, one mile below the mouth of the Paria River. Estimates of the virgin flow have been made for the Upper Basin since 1896; however, the runoff has actually been recorded since the first gauging station was established at Lee Ferry during the summer of 1921. The importance of this flow is accentuated by the Colorado River Compact, which anticipates that the Upper Basin can deliver 75 maf at Lee Ferry each 10 years. Estimates of the long-term annual average flow vary from 11.8 to 16.8 maf depending on the time period selected (see Table 8.1). Others estimate the long-term average to vary from 13.09 to 15.09 maf, again depending on the time period selected (see Table 8.2). Recent tree-ring analysis dating back to 1512 has indicated the long-term mean to be approximately 13.5 maf (Stockton, 1976).

Using his tree-ring indicator study of the Upper Colorado River Basin, Stockton (1976) states that

> The early part of the 20th Century was characterized by a period of anomalously high sustained flow, the longest in the entire 450 year reconstruction.

He goes on to say:

> Based on the foregoing evidence, it is apparent that within Southwestern United States, climatic change has occurred over a fairly short time span and it appears to have been reflected in the annual runoff, at least for the Upper Colorado River Basin.

TABLE 8.1 Colorado River at Lee Ferry, Arizona, Estimated Average Annual Virgin Flowa

Period	Average Annual Virgin Flow (million acre-feet)	Remarks
1896–1968	14.8	73-year period of measured flow and estimates by federal agencies
1896–1929	16.8	34-year “wet period”
1930–1968	13.0	38-year “dry period”
1922–1966	13.8	45-year period of measured flow
1914–1923	18.8	10-year wettest period
1931–1940	11.8	10-year driest period
Total Flow		
1917	24.0	Maximum single year
1934	5.6	Minimum single year

[a] Quantities are for water years October 1-September 30, inclusive. Gauging station established in 1921. Prior to 1922 estimates are based on measurements at upstream stations. (Colorado River Board of California, 1969.)

TABLE 8.2 Estimates of Average Virgin Flow for the Upper Colorado River Basina

Period	Million Acre-Feet per Year
1896–1968	14.82
1906–1965	15.09
1914–1965	14.64
1922–1965	13.87
1931–1965	13.09

[a] *Water Resources Council* (1970), p. v-12.

TABLE 8.3 Colorado River at Lee Ferry, Arizona, Average Five-Year Reconstructed Flow, 1512–1961a

Years	Means[b]
1531–1535	9.6
1553–1557	17.9
1552–1556	17.9
1583–1587	9.0
1589–1593	9.9
1590–1594	8.8
1667–1671	9.2
1912–1916	18.0
1913–1917	19.0
1914–1918	18.4

[a] C. W. Stockton, personal communication (1976).

[b] All mean flows are given in million acre-feet per year.

TABLE 8.4 Colorado River at Lee Ferry, Arizona, Average Ten-Year Reconstructed Flow, 1512–1961a

Years	Means[b]
1548–1557	17.5
1583–1592	9.9
1584–1593	9.7
1585–1594	10.3
1663–1672	10.5
1773–1782	10.5
1908–1917	17.6
1912–1921	17.8
1913–1922	17.8
1914–1923	17.9

[a] C. W. Stockton, personal communication (1976).

[b] All mean flows are given in million acre-feet per year.

The resulting reconstructed flow from tree-ring analysis indicates that the lowest five-year flow at Lee Ferry was 8.8 maf per year, which occurred during 1590– 1594 (see Table 8.3). The lowest ten-year reconstructed flow was 9.7 maf per year, which occurred during 1584– 1593 (see Table 8.4). This 9.7 maf per year flow is not appreciably lower than the 11.8 maf per year 10-year flow that was recorded during 1931–1940 (see Table 8.1).

The current estimates of available surface-water supply within the Upper Basin are less than those at the time the Colorado River Compact was negotiated. This is because of the abnormally wet period that occurred during the early part of this century. The range of annual flow at Lee Ferry has varied from a low of 5.6 maf in 1934 to a high of 24.0 maf in 1917. Some argue that the average flow of 13.1 maf per year that has occurred since 1931 is closer to the long-term mean (Jacoby, 1975a, 1975b).

A Bureau of Reclamation hypothesis indicates that 5.8 maf per year should be used as a conservative amount of water available for consumptive use in the Upper Basin (U.S. Department of the Interior, 1974). Other studies have used different basic assumptions and have applied other factors that have resulted in both higher and lower annual estimates. However, there are undoubtedly those who make different assumptions on the basis of differing interpretations of the impact of the Colorado River Compact.

The amount of water currently being consumptively used in the Upper Basin is approximately 3.7 maf per year. Therefore, 2.1 maf of the conservative 5.8 maf is presently not being utilized (U.S. Department of the Interior, 1974).

The groundwater utilization in the Lower Basin is currently greater than its annual safe yield (Water Resources Council, 1970). Over 60 percent of all withdrawals in the Lower Basin come from groundwater. Annual groundwater pumpage has increased from less than 1 million acre-feet in the early 1930's to currently over 5 million acre-feet. The present annual overdraft is about

2.5 maf, most of which occurs in central Arizona. Whether or not groundwater withdrawal and recharge affect Colorado River Compact commitments is yet to be resolved; however, it does bear on the demand for Colorado River water.

The total water uses that can be derived from these flow estimates vary widely. The Committee on Water (1968) states:

> . . . use of the 13.8 maf estimate . . . would introduce serious doubts of the feasibility of the Central Arizona Project or of an expansion of Upper Basin uses beyond those existing or authorized, or both.

Steiner (1975) claims that if the Upper Basin dedicates this surplus

> . . . to high economic return uses of municipal, industrial and energy development rather than to low economic return agriculture, the remaining entitlement is more than sufficient to meet the needs for energy development in the Upper Basin.

Furthermore, Steiner (1975) argues that the minimum annual release to the Lower Basin at Lee Ferry should be 8.4 maf constituted as follows: 7.5 maf under the Compact agreement, plus 750,000 af as one half of the Mexican Treaty requirements plus 150,000 af as one half of the losses associated with delivery of the Mexican agreement. He contends the latter amount of 150,000 af is arguable, but the remaining 8.25 maf is “crystal clear and inescapable.” This position is supported by California, Nevada, and Arizona (Holburt, 1976).

Since the Upper Basin has a low consumptive use and inability to store water (see Table 8.5), more water has been historically available to the Lower Basin than the law requires. Nevada has a relatively small demand on the water, and Arizona is not using as much of the Colorado River as is its legal allocation. This is because of delays in the construction of the Central Arizona Project. California has facilities to divert more than its legal apportionment and has been doing so (State of California, 1972). However, these diversions are allowed by the documents that make up the “Law of the River.”

TABLE 8.5 Major Reservoirs in Colorado River Basin

			Capacity (million-acre-feet)	
Reservoir	Dam	Stream	Gross	Usable[a]
Upstream of Lee Ferry, Arizona (Upper Basin)				
Fontenelle	Fontenelle	Green River	0.35	0.34
Blue Mesa	Blue Mesa	Gunnison River	0.94	0.83
Morrow Point	Morrow Point	Gunnison River	0.12	0.12
Flaming Gorge	Flaming Gorge	Green River	3.79	3.75
Navajo	Navajo	San Juan River	1.71	1.70
Lake Powell	Glen Canyon	Colorado River	27.00[b]	25.00
Total in Upper Basin			33.91	31.74
Downstream of Lee Ferry, Arizona (Lower Basin)				
Lake Mead	Hoover	Colorado River	28.54	26.16
Lake Mohave	Davis	Colorado River	1.82	1.81
Lake Havasu	Parker	Colorado River	0.65	0.62
Total in Lower Basin			31.01	28.59
TOTAL IN UPPER AND LOWER BASINS	64.92	60.33		

[a] Capacity above dead storage.

[b] Although the capacity of Lake Powell is 27 maf, this quantity has not as yet been realized since filling of the reservoir was initiated in 1963 (Lord, 1976).

WATER AND ENERGY IN THE COLORADO RIVER BASIN

The future key factor in the consumption of water in the Colorado River Basin is the planned and projected energy development, particularly in the Upper Basin.

This proposed energy development in the Basin includes steam-electric nuclear, steam-electric coal, geothermal, natural gas, crude oil, refineries, oil shale, coal mining, coal gasification, coal liquifaction, and coal slurry pipelines. Each of these energy forms requires a consumptive use of water, as indicated in Table 8.6.

This new energy resource development will seek to purchase and convert existing water rights that long have been appropriated for other beneficial purposes. The availability of such rights and the costs of acquisition, development, or both, and the legal constraints will have a major effect on the actual process that will be used in the energy development (Western States Water Council, 1974). An important aspect of this problem is the economic multiplier effects that will be lost to a region if water that is currently being utilized for agricultural development is converted to energy production usage. A summary of pending energy developments in the Upper Basin is shown in Table 8.7. Based on these data, it is estimated that approximately 870,000 acre-feet of water will be needed annually for energy development in the Upper Basin by the year 2000. Subsequent events, however, reveal that these projections for water may be overly optimistic. For example, the Kaiparowits Project in Utah, which was assigned 102,000 af, has been canceled by the Southern California Edison Company. Furthermore, all major oil-shale developments currently have been stopped by private companies pending the resolution of federal loan guarantees and significant environmental problems. All of these rapidly changing factors make any projections of water requirements in the Upper Basin difficult at best. Also, in addition to energy uses, there are other water needs that must be considered. These include municipal, industrial, agricultural, and environmental water needs.

TABLE 8.6 Unit Water Consumption Rates for Energy Resources[a]

Energy System	Water Needs
Steam-electric nuclear	
Evaporative cooling	17,000 acre-ft/yr/1000 mW unit
Pond	12,000 acre-ft/yr/1000 mW unit
River	4,000 acre-ft/yr/1000 mW unit
Wet–dry radiator	2,000 acre-ft/yr/1000 mW unit
Steam-electric coal	
Evaporative cooling	15,000 acre-ft/yr/1000 mW unit
Pond	10,000 acre-ft/yr/1000 mW unit
River	3,600 acre-ft/yr/1000 mW unit
Dry radiator	2,000 acre-ft/yr/1000 mW unit
Geothermal	48,000 acre-ft/yr/1000 mW unit
Natural gas	50,000 acre-ft/yr throughout the West
Crude oil	50,000 acre-ft/yr throughout the West
Refineries	39 gal/bbl/crude
Oil shale	7,600 to 18,900 acre-ft/yr/100,00 barrels per day plant
Coal gasification	10,000 to 45,000 acre-ft/yr/250 million scf per day plant
Coal liquification	20,000 to 130,000 acre-ft/yr/100,000 barrels per day plant
Coal slurry pipeline	20,000 acre-ft/25 million tons coal (1 cfs will transport about 1,000,000 tons per year)
Coal mining	
Vegetation re-establishment	0.5 to 4 acre-ft/acre/yr (some areas may require two years)

[a]Western States Water Council (1974).

TABLE 8.7 Summary of Pending Energy Development, Upper Colorado Basin[a]

State	Coal-Fired Electric Generation	Oil Shale	Coal Gasification	
	(MW)	(KBCD)	(MCFD)	
Wyoming	5,360	125	250	
Colorado	8,970	1,090	—	
Utah	10,630	300	864	
New Mexico	6,850	—	1,788	
Arizona	2,310	—	—	
	34,120	1,515	2,902	
	acre-ft/yr	acre-ft/yr	acre-ft/yr	Total
Wyoming	79,500	22,000	15,000	116,500
Colorado	134,600	191,000	—	325,600
Utah	144,950	46,000	52,500	243,450
New Mexico	82,000	—	72,000	154,000
Arizona	34,100	—	—	34,100
	475,150	259,000	139,500	873,650

[a]U.S. Department of the Interior (1974).

Given that projected water requirements in the Upper Basin will occur, the total depletions in relation to water supply in the year 2000 could be essentially as indicated in Figure 8.2. The individual Upper Basin state depletions and supplies as of 2000 are shown in Figures 8.3 – 8.6. Using these projections, there could be significant shortages occurring in all the Upper Basin states except Wyoming by the year 2000.

The Colorado River Basin Salinity Control Forum

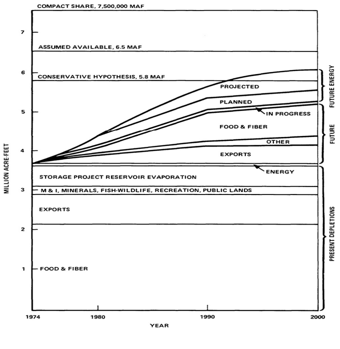


FIGURE 8.2 Upper Colorado River Basin water for energy 1974 to 2000. (After U.S. Department of the Interior, 1974.)

(1975) has made projections on the basis of low, medium, and high rates of water use. These are summarized in Table 8.8. A comparison of these values with Figure 8.2 indicates only a difference of 3 percent between the two projections at the high rates in the year 1990.

Major energy facilities also are being planned for construction in the Lower Basin. It has been estimated that 141,050 acre-feet/year of Lower Basin water will be required for new electrical power generation facilities by 1984 (Jacoby, 1975a, 1975b). However, the fossil-fuel resources of the Lower Basin are nowhere near as great as they are in the Upper Basin; therefore, the stress for *in situ* power production is greater in the Upper Basin.

Dreyfus and Cooper (1974) in their study of "Water and Energy Self-Sufficiency" state that

Upon closer inspection, however, regional water shortage, even in the Colorado Basin, is more prospective than real. The Colorado River system, through a complexity of compacts and water rights, is indeed over-committed in a legal sense. Furthermore, each new consumptive use or degraded return flow adds to the spectre of an ultimate moratorium on any new uses in order to preserve a usable quality for furthest downstream existing rights. The severity of the water resource planning and management problems of the region are undeniable, but the problem is not yet one of physical limitation.

. . . In the Colorado Basin, about 90 percent of all existing water uses are for agriculture, much of it inefficiently applied and producing low value crops. Water for new energy uses quite probably will come, in part, from purchases by energy industries of existing agricultural water rights rather than the development of new supplies. There also exist in the Basin aquifers of considerable size, particularly saline aquifers with little current utility. In some energy applications, such as materials handling, saline groundwater could be used if runoff to surface streams can be prevented.

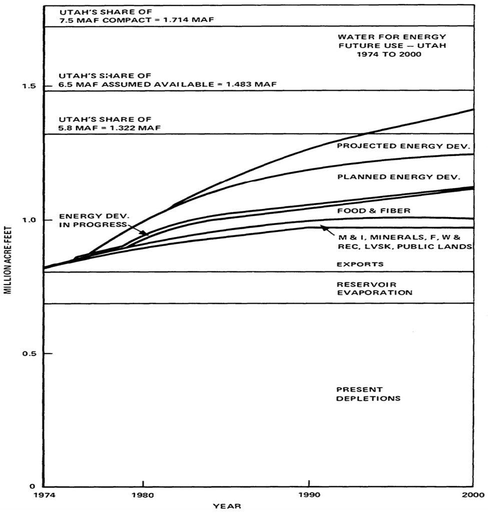


FIGURE 8.3 Water for energy future use. Utah, 1974 to 2000. (After U.S. Department of the Interior, 1974.)

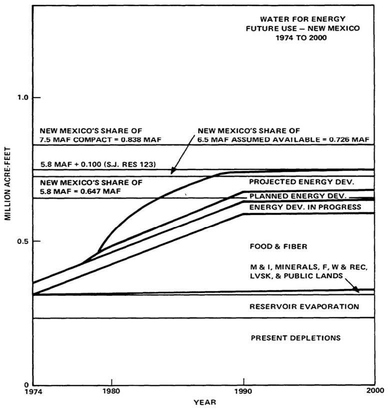


FIGURE 8.4 Water for energy future use. New Mexico, 1974 to 2000. (After U.S. Department of the Interior, 1974.)

In their conclusions they go on to say

There should be a strengthening of Federal activities in river basin planning with a new emphasis on the emerging energy outlook. A national assessment of water for energy, such as has been described, should be initiated immediately and given adequate funding and the highest priority.

FLOW AUGMENTATION

Flow augmentation to the Colorado River Basin is a distinctive technical and perhaps an economic possibility. However, it is fraught with legal, political, social, institutional, financial, and environmental problems and thus may never occur. Nevertheless, some individuals and institutions in the Colorado River Basin support the concept that someday there will be flow augmentation and more water will be economically available to the Colorado River Basin. Four such concepts will be briefly discussed here: (1) water importation, (2) cloud seeding, (3) vegetation management, and (4) sea and brackish water desalination.

Several schemes have been proposed for interbasin diversions to the Colorado River Basin. Diversions from the Snake River Basin are proposed by some individuals and agencies as being a plausible alternative (Dunn, 1964; Nelson, 1964; Bureau of Reclamation and U.S. Corps of Engineers, 1961). However, the Colorado River Basin Project Act of 1968, which authorized the Central Arizona Project, included a 10-year moratorium on ". . . reconnaissance studies of any plan for the importation of water into the Colorado River Basin . . ." (Colorado River Basin Project Act, 1968).

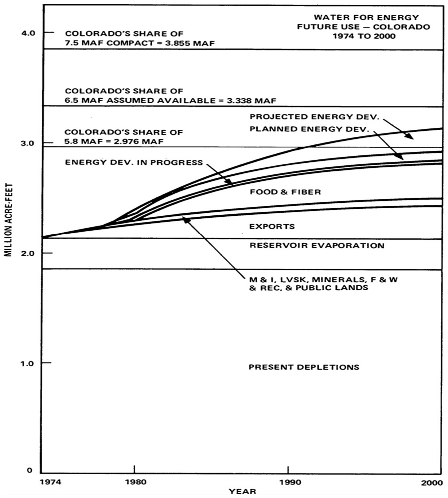


FIGURE 8.5 Water for energy future use. Colorado, 1974 to 2000. (After U.S. Department of the Interior, 1974.)

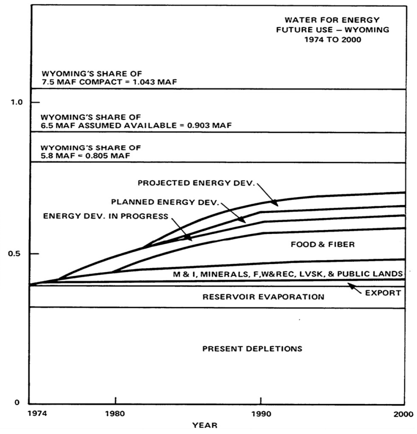


FIGURE 8.6 Water for energy future use. Wyoming, 1974 to 2000. (After U.S. Department of the Interior, 1974.)

The purpose of this moratorium was that the representatives from the Pacific Northwest wished to protect their water resources for local use and to provide a period during which the extent of local requirements could be accurately determined. Therefore, it is yet to be determined whether the importation of water from the Columbia River Basin is a viable alternative for the management of the Colorado River Basin.

Cloud seeding has the distinct advantages of low capital investment, a short response time, and a brief required time for implementation (Redul *et al.,* 1973).

Weisbecker (1974a, 1974b) and Hurley (1967) propose that cloud seeding is a viable method to increase significantly snow storage and the resulting snowmelt runoff in the Colorado River Basin.

However, problems concerning the resulting down-wind effects, the increased probabilities of avalanches, and the increased probabilities of flooding are all important disadvantages. Meteorologists are still uncertain concerning the total effectiveness of cloud seeding (Committee on Atmospheric Sciences, 1966).

The Bureau of Reclamation's July 1974 Project Skywa ter Newsletter reported on the Colorado River Basin Pilot Project. The results indicated the doubtful reliability of weather modification to increase runoff. Furthermore, Weisbecker (1976) reported that the five-year San Juan cloud-seeding program by the Bureau of Reclamation in the Upper Colorado River Basin provided “no significant added precipitation.” In spite of these results, many people strongly believe that weather modification is the panacea for solving the water-supply problems in the Upper Basin. However, certainly in the short run, cloud seeding does not appear to be a viable alternative for significantly increasing the runoff in the Colorado River Basin.

TABLE 8.8 Summary of Estimated Water Use in Colorado River Basin[a,b] (1000 acre-feet)

	1973 Base Condition	Assumption as to Rate of Use	1980	1985	1990
Upper Basin[c]	2976	Low	3,426	3,686	4,111
		Moderate	3,576	4,176	4,594
High	4,021	4,589	5,464		
Lower Basin[d]	6143	Low	5,813	6,238	7,461
		Moderate	5,953	6,838	7,476
High	6,203	8,168	7,500		
TOTAL	9119	Low	9,239	9,924	11,572
		Moderate	9,529	11,014	12,070
High	10,224	12,757	12,964		

[a] Colorado River Basin Salinity Control Forum (1975).

[b] Does not include deliveries to Mexico.

[c] Does not include CRSP reservoir evaporation estimated by the USER to average 520,000 acre-feet per year.

[d] Diversions from the main stem less returns. Does not include main stem reservoir evaporation and stream losses estimated by the Forum to average 1,400,000 acre-feet per year.

The removal of phreatophytes and the management of vegetation in the southwestern United States can result in substantial increases in streamflow (Ffolliott and Thorud, 1974). However, this methodology also can cause increases in salinity, sedimentation, and associated ecological disturbance (Hibbert *et al.,* 1974; Brown *et al.*, 1974). This entire approach can only be implemented when all the land and water resources in the region are considered as a complete ecological system. It would appear that vegetation management could only have limited effect on the Colorado River Basin at the present time.

The desalination of sea and brackish waters also have been considered as a possibility for increased water supply to the Colorado River Basin. However, recent increases in energy costs have resulted in substantial increases in the cost of desalinated water. Therefore, this alternative only is viable in a local context such as the Colorado River International Salinity Control Project (U.S. Department of the Interior, 1973).

It appears from these alternatives that no significant flow augmentation is available in the immediate future.

EFFECTS OF A DROUGHT ON THE COLORADO RIVER BASIN

The picture here has been painted of a limited resource stressed by a myriad of demands and with limited if any sources for augmentation and relief. What happens then if the climatic stress of drought is further added? To answer this question one must include one more important consideration in the analysis. That is, the storage capacities in the entire Basin (see Table 8.5).* Lake Mead behind Hoover Dam in the Lower Basin contains approximately 27 maf of storage capacity. Lake Powell behind Glen Canyon Dam is located just upstream of Lee Ferry. It contains about 80 percent of the total Upper Basin active storage capacity of 33.8 maf (Upper Colorado River Commission, 1970). These are the two main storage reservoirs in the Colorado River Basin, and they have storage capacity in excess of four times the annual flow of the river. Since there is limited storage capacity upstream in the Upper Basin, the current storage capacity configuration obviously favors the Lower Basin.

With this background one can now summarize the following situation in the Colorado River Basin:

1. A system with strong institutional division between the Upper and the Lower Basins.
2. Legal constraints that require certain releases from the Upper to the Lower Basin.
3. A storage configuration that favors the Lower Basin.
4. Extensive energy development projected for the Upper Basin.

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*It should be noted that there is a difference between the storage capacity available and the actual water in storage at any one time.

It would appear, therefore, that any major basinwide drought could have significant and damaging effects on the Upper Basin.

To envisage the extent of damage to the Upper Basin that might occur from such a drought, one should study Figure 8.2. Suppose, for example, the 10-year 1584–1593 drought, which resulted in an average annual flow of 9.7 maf at Lee Ferry, occurred once again. Furthermore, suppose that the maximum available 31 maf of water was stored in the Upper Basin at the onset of the drought. Potentially, a total of 82.5 maf may be legally required to be delivered to the Lower Basin during any 10-year period.* A 10-year drought flow of 97.0 maf would leave the Upper Basin with 14.5 maf plus a potential 31 maf in storage. Thus 45.5 maf would be available to the Upper Basin during this 10-year period, or an average annual amount of approximately 4.6 maf.

From Figure 8.2 it is immediately obvious that such a drought would affect the projected water demands of the Upper Basin if it occurred after 1982.

A myriad of similar scenarios could be considered. For example, during 1931–1940 the average annual flow was 11.8 maf (see Table 8.1). The active storage in the Upper Basin available September 30, 1974, was 23.6 maf (Colorado River Board of California, 1974). Assuming this storage value at the beginning of a 11.8 maf total 10-year flow and an 82.5 maf 10-year delivery to the Lower Basin leaves the Upper Basin with 59.1 maf available during this 10-year period, or an average annual amount of approximately 5.9 maf. Again from Figure 8.2, it is obvious that such a drought would affect the projected water demands of the Upper Basin if it occurred after 1992.

Much of this water is projected to meet the needs of expanding food, fiber, and energy development. The energy demand for water is not seasonal, as irrigation and municipal water supply demands, but requires a relatively constant year-round supply. Since those energy projects are such capital-intensive developments, it seems foolhardy to continue with these projects without a guaranteed annual water supply in the face of a severe drought.

Mitigating circumstances are considerations of specific locations of each of the energy projects in the Upper Basin and their adjacent water supplies. That is, the macroview of the Upper Basin distinctively indicates significant future shortages under a drought condition. However, the microview of each project may be less severe in some cases. This analysis remains to be completed elsewhere.

Further work that needs to be accomplished includes the consideration of scenarios of 3-, 5-, 7-, and 10-year droughts in the Upper Basin and an evaluation of their macroeconomic and microeconomic effects on the region and the nation.

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*Ten-year totals of 75 maf under the compact agreement plus 7.5 maf as one half of the Mexican agreement. (Note: The Lower Basin states contend that 84 maf would be required during this period, and the Upper Basin states contend that 75 maf would be required.)

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