Proceedings of the
First National Conference on

Climate Change and Water Resources Management

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Editors:

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U.S. Army Corps of Engineers

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REPLY TO ATTENTION OF

June 24, 1994

CEWRC-IWR

MEMORANDUM FOR COMMANDER, Defense Technical Information Center, Cameron Station, Alexandria, VA 22314

SUBJECT: Transmittal of IWR Report 93-R-17

1. Reference AR 70-31.

2. Two copies of IWR Report 93-R-17, "Proceedings of the Forst National Conference on Climate Change and Water Resources Management", has hereby been submitted.

3. Initial distribution of this report has been made to appropriate Corps of Engineers agencies. It is recommended that copies of this report be forwarded to the National Technical Information Center.

4. Request for the DTIC Form 50 (Incl 2) be completed and returned to WRSC-IWR.

FOR THE DIRECTOR:

Enclosure

Kyle E. Schilling
Director

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National Wildlife Federation
The Electric Power Research Institute
Water Pollution Control Federation
Water Quality 2000

INTRODUCTORY REMARKS BY CONFERENCE CHAIRMAN

Mr. Kenneth H. Murdock, director of the U.S. Army Corps of Engineers Water Resources Center, opened the conference. Mr. Murdock reviewed the historical interest of the Corps of Engineers in water resources management under highly variable contemporary climate conditions and suggested that these variations serve as a precursor to those created by potential climate change. He described the research programs of the Institute for Water Resources and the Hydrologic Engineering Center, which include important work on the economic impacts of global warming on the water resources management and shore protection responsibilities of the U.S. Army Corps of Engineers. The results of these studies provide the basis for the continual adaptation and refinement of the Corps planning, design, evaluation, and operations procedures and for development of future Corps policies. In addition, the Corps has been participating in several working groups of the Intergovernmental Panel on Climate Change sponsored by the United Nations. Mr. Murdock continued by acknowledging the conflicts and complexity of the debate surrounding climate change issues. He praised the work done by federal agencies and other organizations that are concerned with those problems and the bewildering range of response actions that could be taken at various levels of government, both at the national and international levels.

With a subject as complex as this one is, many issues have not received the attention they deserve. Consequently, this conference was designed to focus on those areas related to the best current thinking on the potential sensitivity of water resources to climate change and shifts in climate variability. The presentations are organized to elicit the views of practicing water resource managers, planners, and policy makers in an effort to get beyond the abstract rhetoric and begin to focus on problem-solving. Some of those subjects are: What would climate change mean to water management? How do we determine if the threat is real? What are the risk factors, when and where might these factors occur, and what problems and opportunities does this uncertainty offer? The conference was designed to learn from practicing water engineers and planners how they are currently responding to the information available to them and what information they would need in order to directly integrate climate change considerations into their operating and investment decisions.

PREFACE

In late 1991 a group of highly respected climate modelers, water resources scientists, and water managers gathered in Albuquerque, New Mexico, to consider the complex issues that are related to climate change and impacts that such change may have on water resources management. The two and a half day conference was the brainchild of Mr. Joel Smith, who at that time was Deputy Director, Office of Policy and Planning Evaluation, U.S. Environmental Protection Agency. He was successful in obtaining the co-sponsorship of the five federal agencies that have primary water resources development, management, regulation, and data collection missions. Representatives of the U.S. Army Corps of Engineers, Bureau of Reclamation, U.S. Geological Survey, and National Weather Service, together with the U.S. Environmental Protection Agency, comprised the steering committee that organized the conference. Support was provided by 11 nongovernmental associations and organizations that are involved with water issues. The names of those organizations and acknowledgement of their support can be found printed inside the front cover of this document.

The stage for this conference was set with the publication of several important documents--the United Nations Intergovernmental Panel on Climate Change (IPCC) reports on the impacts of climate change and the American Association for the Advancement of Science (AAAS) book on water resources and climate change. The conceptual scientific and policy foundations for a more informed discourse on the implications of climate change to practicing engineers, planners, and water managers were now available. What was needed was a practical assessment of what information the professional water management community needed for decision-making.

The idea to hold this conference was developed from a belief on the part of the organizers that too little attention has been given to the views and needs of water managers in the ongoing public discourse on adaptation to potential global warming. Professor Pete Rogers puts it succinctly in a statement in his paper entitled "What Water Managers and Planners Need To Know about Climate Change and Water Resources Management," found in the first section of this proceedings:

> Water resources managers and planners generally consider two types of decisions: those dealing with new investments and those dealing with the operation and maintenance of existing systems. A third category that falls between these two, and that is becoming more important recently in the U.S., is that of investments that modify the operational capacity of existing systems. In order to inform these decisions, information is needed about future availability of water and future demands for water. Both availability and demand are affected by climate change. On the supply side, water planners and managers would like to know the predicted average precipitation and other climate parameters and some estimates on their variability at a scale of small watersheds. On the demand side, they would like to know how water use would be affected by climate change.

The conference was convened to address those issues. This volume contains papers presented at the conference by scientists and water resource managers whose collected perspectives represent the best current thinking on the subject. The structure of the conference was designed to emphasize both practical and conceptual issues, hydrology, and water management amidst a diversity of geographical regions and response strategies. In addition, two plenary sessions were devoted to broader subjects of formulating responses to potentially critical problems.

The first of those two sessions framed the debate and discussion of response to climate change as it may be influenced by developing scientific, political, economic, institutional, environmental, and associated issues, conditions, and determinants. The papers presented and the ensuing discussion addressed the important scientific debate on questions surrounding whether or not mankind is causing global warming and, if so, how are policy, business, and political decisions being influenced. The roster of speakers included those who contend there is overwhelming evidence that global warming is occurring and others who note that, while this may be true, the variability in the current climate regime is so great as to mask any detectable signal of change in the near future. The possibility of climate change introduces an entire raft of uncertainties into the water resources management decision-making process. Those who are involved need to understand the effects that these uncertainties have on water resources planning, design, and operations; on management of water resources systems; and on the changes in dynamics of water supply and demand that may occur. With the stage set, successive groups of speakers from the West, Southeast, Northeast, and Upper Midwest presented and interpreted these issues within the context of water resources management practices in their geographic regions.

The papers presented in the second plenary session addressed questions concerning assessments based on General Circulation Models (GCM), attempts to improve accuracy in predictions generated by the models, and the relevance of model outputs to practical engineering solutions. Weaknesses in the results being produced by models, which do not yet accurately portray physical systems, are the result of a concentration of too many assumptions, simplifications, and extrapolations. While the outcomes are as yet ambiguous, they suggest certain tendencies that require the attention of water resource managers. However weak, models do uniformly demonstrate increased atmospheric temperatures that may translate into potentially adverse effects on society. Studies suggest self-evident truths that water managers should plan to implement actions that can be supported under current evaluation criteria even without climate change. The possibility of climate change merely adds further impetus to the implementation of such options. A speaker addressing the issue of uncertainty advocated development of interactive land/surface models with ocean/atmospherc models to overcome some of the many remaining uncertainties. While scientists labor over models, there is little understanding among water resources engineers, much less the public, of their outputs or of how much uncertainty can be attributed to differences in estimates of the model parameters, how much to data, and finally how much to differences in interpretation. Following the plenary presentations, speakers covered various adaptive responses to climate change through the use of long range planning, demand management, supply development and management, and response to extreme events.

The closing panel discussion addressed climate change and water resources management through the use of a series of three questions that were posed to the panel members. The questions concerned: (1) the likelihood of change and its importance; (2) information scientists should provide to substantiate change; and (3) measures to undertake now in planning and responding to climate change. The panelists supported positions and were generally in agreement that climate change would occur and that more information, such as that which could be generated through multi-objective basin planning, is needed. However, our water resource systems have the ability to change operations to adapt to changing situations--what the professionals call robustness and resiliency. The water industry is under pressure to comply with increasing legal requirements which consume financial resources that could be allocated elsewhere. Others suggested that while climate change has become a national political focal point, it is not on the local political or professional agendas in the United States. Therefore, response to possible climate change lacks a widespread understanding as well as popular support and it continues to be a major challenge confronting public and private organizations.

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WHAT WATER MANAGERS AND PLANNERS NEED TO KNOW ABOUT CLIMATE CHANGE AND WATER RESOURCES MANAGEMENT

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ABSTRACT

Water resources managers and planners broadly deal with two types of decisions: those dealing mainly with new investments and those dealing with the operation and maintenance of existing systems. A third category that falls between these two, and that is becoming more important recently in the United States, is that of investments that modify the operational capacity of existing systems. In order to inform these decisions, information is needed about future availability of water and the future demands for water. Both availability and demand are affected by climate change. On the supply side, the water planners and managers would like to know the predicted average precipitation and other climate parameters and some estimates of their variability at a scale of first-order watersheds (typically about 30 km by 30 km). On the demand side, they would also like to know how water use would be affected at the same physical scale.

Time plays an important part in water resources policy investment decisions. With an average lead time of 28 years from start of planning to completion of projects in the United States, any new water project with a 50-year life would still be functioning in the year 2070. This is within the time frame when climate changes are predicted to become noticeable. Hence, the dynamics of water supply and demand changes are important information.

The social context within which the decisions are to be made is also of paramount importance in making the decisions. The social acceptance of various engineering projects conditions how engineers will think about and plan various options. There is therefore a need to be able to predict the changing social contexts associated with climate change.

This paper concludes that water managers and planners need to know a lot more about future demands and supplies of water than can realistically be provided by climatologists. Essentially the information required cannot be predicted by physical-science methods alone; economic and social adjustments predominate in responding to water use. Hence, water managers "are on their own" until such information becomes available and will have to rely upon their own remarkably successful stochastically robust methods of dealing with information-poor environments.

INTRODUCTION

It is now fashionable to get a laugh at the expense of climate modelers; either at the naivete of their models or at the poor quality of their predictions. In this paper I intend to do neither; not that I think that the modelers are doing a particularly good job but, rather, because I believe that the typical large climate models are irrelevant to my topic--namely--what do engineers need to know about climate change? Even if the models were scientifically well grounded and their predictions were considered to be perfect, I still maintain that they are largely irrelevant to practical engineering decisions. These may appear to be strong claims but I hope to be able to convince you of their validity.

The main thrust of my argument is that water resources planning is *not* simply a scientific activity. Water resources planning is a broad political, economic, sociological, scientific, and technological endeavor. To assume *a priori* that the present and future quantity of water available is the only, or even the major, determinant of the outcomes is incorrect. I maintain that there are other sources of uncertainty that are of such large magnitudes relative to the uncertainties in water supply that they, rather than water, should dominate our choices of action. In my paper I call your attention to a couple of case studies that I believe will convince you that predicted water availability should not necessarily be the most important parameter in water resources planning and management.

In the audience today are several colleagues who participated in a recent book entitled, *Climate Change and U.S. Water Resources*, edited by Paul Waggoner (1990) under the spiritual guidance of the late Roger Revelle. For others in the audience who have not had a chance to read this book I would urge you to do so. It is a wise book that reviews the evidence dispassionately and looks critically and creatively at the prognoses for the future. For my colleagues on that book let me say that there is a great advantage to being on the conference program early; I can pick and choose freely from the book without it appearing repetitious to most of the audience. I sincerely hope that you will not feel constrained to have to rewrite your own papers on the basis of my remarks.

Also sitting in the audience today are several authors of the 1977 National Research Council's study entitled *Climate, Climatic Change, and Water Supply*. Indeed, it is no surprise that the sets of authors overlap to a large extent. What is quite surprising is the "shelf life" of the 1977 study. In many areas we seem to be no further along than we were in 1977. More important, the climatological parameters that the 1977 authors wished they had are still, by and large, not available--or not even on the horizon. The intervening 13 years has not brought water planners and managers better estimates of potential changes in means and variance of precipitation. The 1990 book was still limited to assuming levels of precipitation change and restricted still to "what if" types of statements.

With this cautionary tale in mind, I can think of no better place to start my paper than with an admonition from Waggoner et al.:

> Those reporting about climate change bear a special responsibility for accuracy, conveying the real complexities and uncertainties, and not oversimplifying. Scientists must make extra effort to explain clearly in conservative and understandable terms (Waggoner, 1990, p. 6).

WATER RESOURCES PLANNING AND MANAGEMENT

Water resources managers and planners generally consider two types of decisions: those dealing mainly with new investments and those dealing with the operation and maintenance of existing systems. A third category that falls between these two, and that is becoming more important recently in the United States, is that of investments that modify the operational capacity of existing systems. In order to inform these decisions, information is needed about future *availability* of water and the future *demands* for water. Both availability and demand are affected by climate change. On the supply side, water planners and managers would like to know the predicted average precipitation and other climate parameters and some estimates of their variability at a scale of small watersheds (about 30 km by 30 km). (Giorgi and Mearns (1991) indicate that it would currently take 2 days of computing time to simulate 1 day of climate at this scale using a Cray X-MP computer. A 50-year forecast would, hence, require 100 years of real time--not a very helpful situation.) On the demand side, they would like to know how water use would be affected by climate change.

Time plays an important part in water resources policy investment decisions. With an average lead time of 28 years from start of planning to completion of large multi-purpose projects in the United States, any water project currently under consideration with a project life of 50 years would still be viable in the year 2070. This is within the time frame when climate changes are predicted to become noticeable. Hence, the dynamics of water supply and demand changes ought to be important information.

SOURCES OF UNCERTAINTY IN WATER RESOURCES PLANNING

In a greatly unappreciated paper, James, Bower, and Matalas (1969) analyzed the relative importance of different kinds of variables in water resources planning. They assessed the relative importance of four types of input variables covering four areas of disciplinary concern: hydrology, environmental response, choice of planning goals, and economics. Their paper has a lot to tell water resources planners and managers of the 1990s as we struggle with what to do about potential or predicted climate change. I will use their definition of the concerns of water planners:

> Water resources planning in the context of investment decisions involves the determination of how much to spend for capital, operation, and maintenance costs over time for what structural and nonstructural measures, when, and where. The objective of such planning is to decide the size, type, location, and method of operation of facilities and the points in time that they will have to be in operation, in conjunction with the type, size, location, timing, and method of operation of related structures (James et al., 1969, p. 1165).

When dealing with water resources essentially three things should be known: the future availability of water, the future demand for water, and the consequences that both of these have on the environment. Unfortunately, each of these unknowns is knowable only to some level of certainty. Climate change is just one of several factors that make precise prediction impossible.

CAPACITY EXPANSION: THE PROBLEM WITH TIME HORIZONS

Many water resources planning problems encountered may be categorized as "capacity expansion" problems. Typically these problems are of the type where there is a demand for increasing additional water supplies over some time period. The goal is to meet this demand over time at least cost. The Potomac case mentioned later is a classic example of this type of problem. While this problem is common to many other industries, such as electric power, an analytic approach to single-purpose water projects was first formulated by Harold Thomas (1971). The problem of capacity expansion can be viewed as a series of sequential decisions of how much excess capacity to build into the system to meet the future demands. Figure 1 shows a typical view of a "staircase" of future investment in excess capacity.

The simplest case that assumes linearly increasing demands and no shortages is still a difficult problem to solve analytically for the size of the next investment (and, hence, all succeeding ones since the staircase repeats itself ad infinitum). Thomas derived a solution in terms of the number of years of excess capacity to be built, τ, as follows;

$$\tau^{*} = \frac{6}{r}(1 - b^{1/3}) \qquad (1)$$

The implications of this result for planning water resources can be quite startling. Equation (1) tells us that the optimal time horizon is independent of the rate of growth in demand and independent of magnitude of the capital costs. It depends solely upon the discount rate, r, and the economies of scale parameter, b.

The economies-of-scale parameter ranges from 0 to 1, where unity implies that there are no economies of scale and that there is no incentive to plan for more than 1 year at a time. From equation (1), the optimal excess capacity is 0--do not build ahead of demand. A typical value of b for large engineering structures is in the range of 0.5 to 0.8. The smaller the value of b, the larger the economies of scale and the longer into the future one plans.

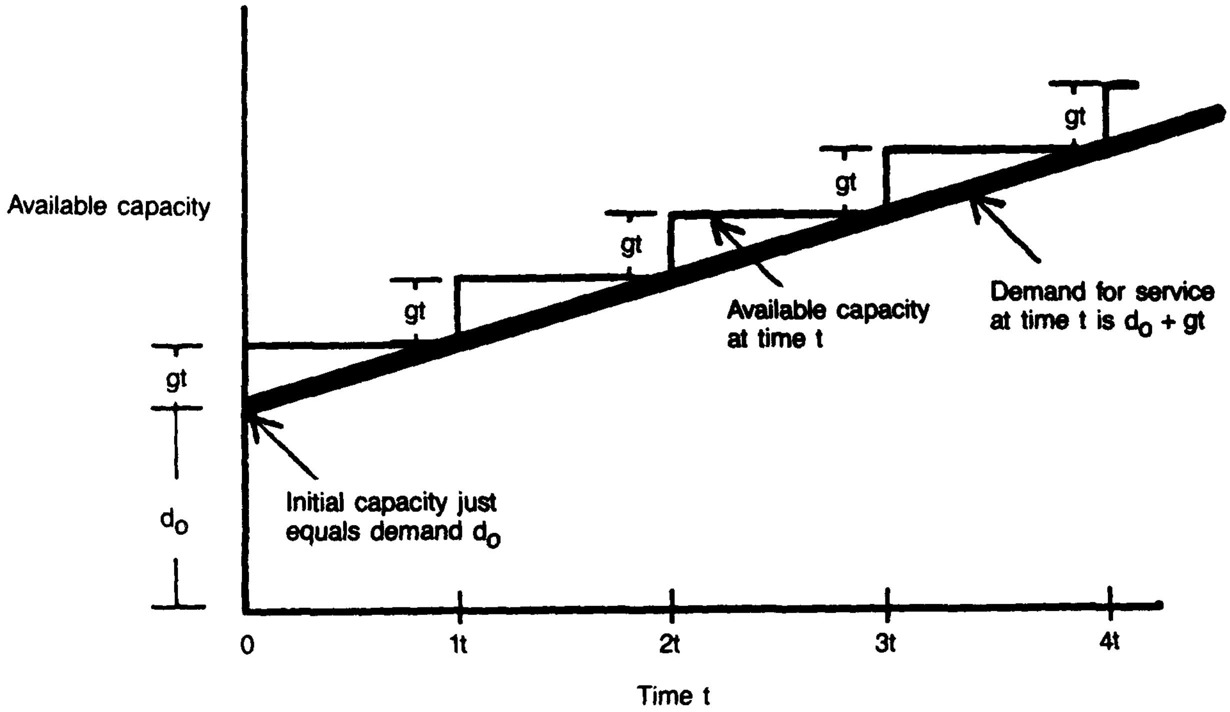

Figure 1. **Capacity expansion in water systems.**

The functional form of equation (1) is a surprise. (For the case of geometric demand growth this is strictly not true. However, Muhich (1966) showed computationally that over the range of traditional discount rates the optimal time horizon was essentially independent of the rate of growth of demand and was mainly a function of the discount rate. Many other cases involving linear and geometric demand growth with various possibilities for shortage have since been considered in the literature. See Fallon (1986) for a useful review of this literature.) Less surprisingly, when the discount rate, r, is high the optimal planning horizon should be short. Examples given by Thomas, based upon plausible costs and economies-of-scale parameters for water infrastructure, imply that when the discount rate is 3 percent we should plan for 41 years of growth in demand, and when the discount rate rises to 10 percent, we should plan for only 12.4 years into the future. This simple model explains why public water planners feel quite comfortable with the 40-year planning horizon but feel very uncomfortable with 12-year planning horizons and the private-sector water planners feel exactly the opposite.

These results quoted above should be tempered, however, with some practical considerations that are not included in the models: transaction costs. Even though no costs enter into equation (1), bureaucratic and political considerations may make the total cost of the project much more lumpy, hence decreasing the economies-of-scale parameter and making larger size more attractive than the simple model would suggest.

The implications for planning under climate change should now become quite clear: for most cost functions, demand forecasts, and discount rates the optimal plan is to plan for quite short periods into the future. *So the future is not far away*. Hence, forecasts of major changes happening over 40 to 50 years will not have any impact upon the rational optimal choice now.

The situation changes when uncertainty is introduced into the parameters of the capacity expansion model. For example, a 25 percent underestimate of the discount rate gives an optimal design period moving from 41 down to 33 years and, similarly, a 25 percent overestimate makes the error move in the opposite direction to 55 years. How well do we know which is the "correct" discount parameter? Errors of the same magnitude in estimating the scaling parameter as those reported above for the discount rate cause even larger errors in the time scale for the project. However, given the state of engineering cost accounting, there is no reason to think that the estimation errors for the scaling parameter will be anywhere as large as the estimates of the discount rate, which involves complex social judgments.

SOME CASES

For the purposes of this paper, I have chosen two cases that span the United States from the humid East to the arid West. They also deal with water supply and water quality. One deals with a reassessment of a series of proposed investments and the other deals with the operation and management of a large system under severe stress due to drought. There are many aspects of water resources planning and management that are not explicitly covered by these two cases, nevertheless I believe that the cases presented will advance my argument.

The Potomac River Basin

James, Bower, and Matalas (1969) considered the Potomac River basin as a case study. This was a particularly fortunate choice since over the intervening 22 years a series of decisions and plans have actually been implemented in the Potomac basin and can be used as a test of the conclusions in their paper. The basin was also the focus of one of the chapters in the 1977 National Research Council's study (Schwarz, 1977).

In 1963 the U.S. Army Corps of Engineers recommended that 16 major reservoirs costing $400 million and 418 headwater reservoirs costing a further $100 million be built in the basin (U.S. Army Engineer District, 1963). Nine of the major reservoirs were recommended for immediate authorization in order to meet flow requirements and water quality improvements by 1985-1990.

The details of the actual implementation of the Potomac plan are given in Sheer (1986). The important point is that eventually only one small water supply reservoir was built. The water supply goals and the greatly improved water quality goals were met mainly by operating the existing separate systems more efficiently as one large system, and by implementing the federal Clean Water Act of 1972. This is a cautionary tale and should be borne in mind by those who would have us make important decisions before we have understood the full implications of the relative uncertainties in the system.

James, Bower, and Matalas used four-way analysis of variance on the output of a simulation model of the basin that was run under different sets of assumptions regarding the various types of input variables. The model, like many such river basin simulation models, dealt with the hydrologic uncertainty in great detail simulating 1,000 years of monthly flow data for each of 30 sites around the basin. The environmental response was assessed using two models, one basically using 5-day biochemical oxygen demand (BOD) concentrations as an indicator of environmental damage, and one using the ultimate oxygen demand with much more attention to the impacts in the estuary. The economic inputs were limited to forecasts of waste load and water demand made by the Corps of Engineers and a version of it in which the total demands were scaled down by 25 percent. The political goal-setting input was characterized by setting as goals two levels of dissolved oxygen in the river and estuary. From the point of view of total number of months failing to meet the dissolved oxygen target, they found that the most important input variables were the *economic* variables followed by the *political* variables. Trailing far behind these was the environmental response; the hydrology was the least important.

In the spirit of the admonishment given above, one should be careful to indicate that these results were based upon a particular set of simulation models with specific assumptions regarding the types and ranges of uncertainty for each of the major factors or variable types. Nevertheless, what actually happened between 1963 and

1991 seems to bear out the major conclusions of the James, Bower, and Matalas study; the reliability and variability of the water availability was swamped by the uncertainties in the political and economic factors, which meant that the dire predictions of the original Corps report did not come to pass. The political will to interconnect and run the system as a whole was the most important factor missing from the original plans. Incidentally, the only set of variables that did not change significantly was that of the hydrology.

In the 1977 report, Schwarz carried out an analysis of the Potomac basin water supply to assess the potential impact of climate change. He created his own simulation model and simulated the performance of the system, measured this time in terms of the reliability in meeting the water supply targets. (By 1977, water quality was no longer the major concern because of the implementation of the Clean Water Act of 1972.) He discovered that even though the scenarios for possible climate outcomes gave a range of hydrologic outcomes with large extremes and wide ranges in the streamflows, when these flows were put into the water system model, the outcomes were greatly buffered. This is a point often overlooked in the discussion of the effect of climate change on water resources; it is not the change in flows that is important but the economic consequences associated with those flows. Schwarz's conclusion is worth repeating:

> The result of this analysis was generally disappointing to those who believe that climate change should radically alter the water supply planning process....If, in addition, we add in the uncertainty of the timing of possible climate changes, then it becomes even more certain that current planning does not have to be concerned with climatic change (Schwarz, 1977, p.118).

In *Climate Change and U.S. Water Resources*, Schwarz returned to this theme (Schwarz and Dillard, 1990) with case studies of the perceptions of the managers of several large water utilities (in Indianapolis, New Orleans, New York, Salt Lake City, Tucson, Washington, D.C., and Worcester (Massachusetts)). In each case he found that the managers and planners questioned were taking a "wait and see" approach. Some, notably those in New York City, had already carried out studies of the consequences of climate change on their systems. Apart from some concern with coastal flooding due to sea-level rise, all the utilities believed that they could easily and relatively cheaply adapt to climate change when and if it came. All were waiting to see if a scientific consensus would emerge before they had to act.

Based upon his experience with the Potomac basin, Dan Sheer (1986) has since unearthed several other cases in which joint management of water supplies could lead to large increases in water availabilities. For example, in Houston, Texas, Sheer estimates that conjunctive use of surface and groundwater could increase system yields by 20 percent even though both sources are already highly developed, and joint management of the water supplies on the Platte River could reduce water shortages by 30 percent, even permitting additional water withdrawals. This type of management could make all of the difference in situations where the streamflows had been impacted by climate change. So far most of the adaptation discussed has been by improving management of the resource in the face of uncertainty. This could be characterized as *supply-side* management. As we have seen, large expansions of supply (at given levels of reliability) are possible quite inexpensively. The newer aspects of water management are on the *demand side*. The following is an example of the potential for large reductions in demand.

The California Drought

Later in the program you will hear much more about the California drought from the local experts. Nevertheless, I want to comment on it to bolster my argument about what managers and planners can do. The current 5-year drought in California provides us with some excellent material on how hard, or how easy, it is for large water-using systems to respond to large and persistent changes in water availabilities. The drought provides us with a natural laboratory within which we can study potential climate change almost like a scientist would perform a controlled experiment. In the applied sciences and the applied social sciences (both critical for water planners), we rarely have the opportunity to follow such "experiments." One nice feature is that the drought is stimulating a whole new literature on water users' and water planners' responses to shortages. Four noteworthy papers are those of Becker, Cody, and White (1991), Gleick and Nash (1991), Kennedy (1991), and Peabody et al., (1991).

As Director of California's Department of Water Resources, Kennedy was in charge of suggesting remedies for the crisis. The years 1987 through 1991 were the four driest on record for much of the state. By the beginning of 1991, urban areas were facing as much as a 50 percent shortage of water. In early February the State Water Project reduced urban water deliveries to 10 percent of normal supply (a 90 percent reduction) and eliminated all agricultural deliveries. At that time the state was two-thirds of the way through the rainfall season and it was the driest year on record. There were calls in the media and from citizens' groups for the new governor, Pete Wilson, to declare a statewide emergency and reallocate all of the water regardless of ownership (under state law the governor has the authority to take property but the state has to compensate for it). Frightened by the prospect of multi-billion-dollar litigation, the top officials decided instead to institute a Drought Water Bank. The bank was instructed to purchase water from farmers and then resell it to those with the most pressing needs. There was to be no coercion; all purchases and sales were to be voluntary. After much discussion it was agreed to offer $125 per acre-foot of water to the sellers with the hope of obtaining between 750,000 and 1 million acre-feet of water and selling it to whomever wanted it at $175 per acre-foot.

As of the end of June 1991, the Drought Water Bank had purchased about 750,000 acre-feet of water: 400,000 from fallow farmland, 210,000 from groundwater sources, and 140,000 from surface reservoirs. This was derived from 340 separate water sales contracts. It was a surprise to many people that such large quantities of water became available so quickly. The bank is considered a success for this year, but despite improved rains the water situation for next year is uncertain. There is talk of making this temporary bank a permanent feature in California's water system. However, such a development would probably run into multi-year negotiations about the permanent transfer of water rights and the resolution of potential third-party impacts. Kennedy claims that because of the crisis situation they were able to move quickly and decisively, which he believes may not be the case in anything less than a full drought situation.

Becker et al. (1991) concentrated upon the effect of the drought on agriculture and natural resources and concluded that the California agricultural industry had been able to cope well with the first 4 years of the drought due to its flexible system of delivery of alternative sources of water. However, increasing reliance on groundwater was causing rapid declines in the water tables in many areas and could not be sustained for many more seasons. Fish, wildlife, and forests have been severely impacted by the drought. Gleick and Nash (1991), who you will hear from later today, examined the environmental and societal costs of the drought and analyzed its indirect impacts. They claim that the greatest impacts have been on the environment, that many of the ecological effects may be irreversible (for example, on the delta smelt, *hypomesus transpacificus*), and that while the direct impact upon agriculture is likely to be only around 2 percent of the total agricultural income ($18 billion), substantial economic costs (an additional $3 billion over the 5 years of the drought) will be borne because of decreased hydroelectric potential and loss of tourism (during the 1990-1991 season, ski resorts reportedly lost about $85 million).

Peabody and his collaborators (1991) took a broader look at the problem of water shortages as a permanent feature of the California water planning scene. The drought is only incidental to their much wider exploration of water use. The subtitle to their report is "Water Resource Management in a Closing Water System." The concept of a "closing system" is of interest because instead of focusing on ways to expand water supply, they focus upon exploring ways to make better use of the existing water supplies (demand management).

> ...in a closing system, all users become increasingly interdependent. Each use of water either reduces or increases the relative supply for someone downstream, by reducing the quantity or quality of the water that is discharged. Management of the interdependence becomes a public function. Ultimately, a closing water system requires much more management than an open system....The difficult part of managing a closing system is the development of mechanisms to get all users to acknowledge their interdependence and to engage them in a negotiation process that binds them to the agreements reached (Peabody, 1991, p. 7).

In addition to the emergency Drought Water Bank, they also discussed four other approaches to making better use of the existing water supplies: conservation and rural/urban water transfers (the agreement between the Imperial Irrigation District and the Metropolitan Water District that promotes the transfer of water conserved in the Imperial Valley to the Los Angeles region); conservation via pricing (Broadview Water District's tiered pricing program); water storage and exchange (the Arvin-Edison/ Metropolitan Water District's agreement to use a rural aquifer to store temporarily urban water supplies); and the expansion of intersectoral dialogues between users from different sectors (the Three-Way Water Agreement Process between the Pardee group and the Hetch Hetchy group).

Gleick and Nash examined the proposition of the "drought as analogue of climate change," and concluded that, while an imperfect analogue, it does demonstrate the vulnerability of the economy and the environment of California to variations in climate. Surprisingly, after describing the quite remarkable adaptations made by Californians to much greater impacts than typically predicted by the climate models, they claim that the responses would not be adequate to cope with actual climate warming. On the contrary, Peabody and his colleagues are quite optimistic about the prospects for adaptations by the various water users in California in the face of a "closing water system."

To a reader with an historical inclination, all of the California studies have a hollow ring. Each study, in its own way, indicates the remarkable adaptations that have occurred and are occurring in response to the 5-year drought of 1987-1992. What I worry about is how much adaptability the California water system has to the *100-year drought that could occur*. From 1750 to 1850, the century preceding U.S. control of that state, a 100-year drought occurred in California (Bredehoeft, 1984). Ever since 1850 the state has been in an unusually wet period. This is the period of the intensive economic development of the region. How many more years into the future could California keep ahead of the supply limitation by demand management of the type recently practiced? One does not need the threat of climate change to be quite concerned about the water supply in California.

CONCLUSIONS

Water managers and planners face many uncertainties. It appears from the cases reported in this paper that the hydrologic ones may be among some of the least important. (At the conference, information was provided about a 25 cm sea-level rise in the Delaware Estuary over the course of this century. This is about the same magnitude as expected sea-level rise with a doubling of CO_2. That the actual rise was accommodated without major crises indicates that sea-level rise can be dealt with by society by easy adjustments.) Nevertheless, water is and will remain a critically important resource for maintaining ecosystems and economies. It appears to me that the two most important parameters that water managers need to get from climatologists are the potential magnitudes of future water supply and its variability. The Potomac case makes clear that managing the variability of the supply is the most important aspect of planning. Therefore, if the climate experts were able to give us accurate estimates of the changes in the means, variances, skewness, and persistence of either the precipitation or the streamflows, then conceptually we could improve our plans for meeting future demands.

The situation appears almost trivially obvious until one looks at actual cases. Figure 2 (Parry and Carter, 1986) shows what happens when the mean of a probability distribution of streamflows is decreased and the variability increased. Information of this type *ought* to be very useful to the water planner, however, consider how the information that the mean streamflow would decrease by 20 percent and that the standard deviation would increase by 10 percent over a period of 60 years would be viewed by a typical water manager. (This is at the extreme levels of predicted outcomes from climate change in the United States. For example, for the Colorado, Nash and Gleick (1991) reduced the earlier predictions of declines in annual flow from over 40 percent to between 14 and 23 percent for a 2°C temperature rise coupled with a 10 percent decrease in precipitation.) He or she would estimate the likely flows over the next 60 years using some sort of stochastic simulation model and obtain results similar to those shown in Figure 3 (plotted for only 5 of the many thousand simulations) based upon actual river flow data. Unfortunately, Figure 3 is much more complex than Figure 2. Even though we know *exactly* the change in climate, at least for about the first 40 years of the new time series, the decisions the manager would make would be no different than if he or she had not been presented the new information. Given the argument for shorter rather than longer planning periods in Thomas' work, the new information is *largely irrelevant*.

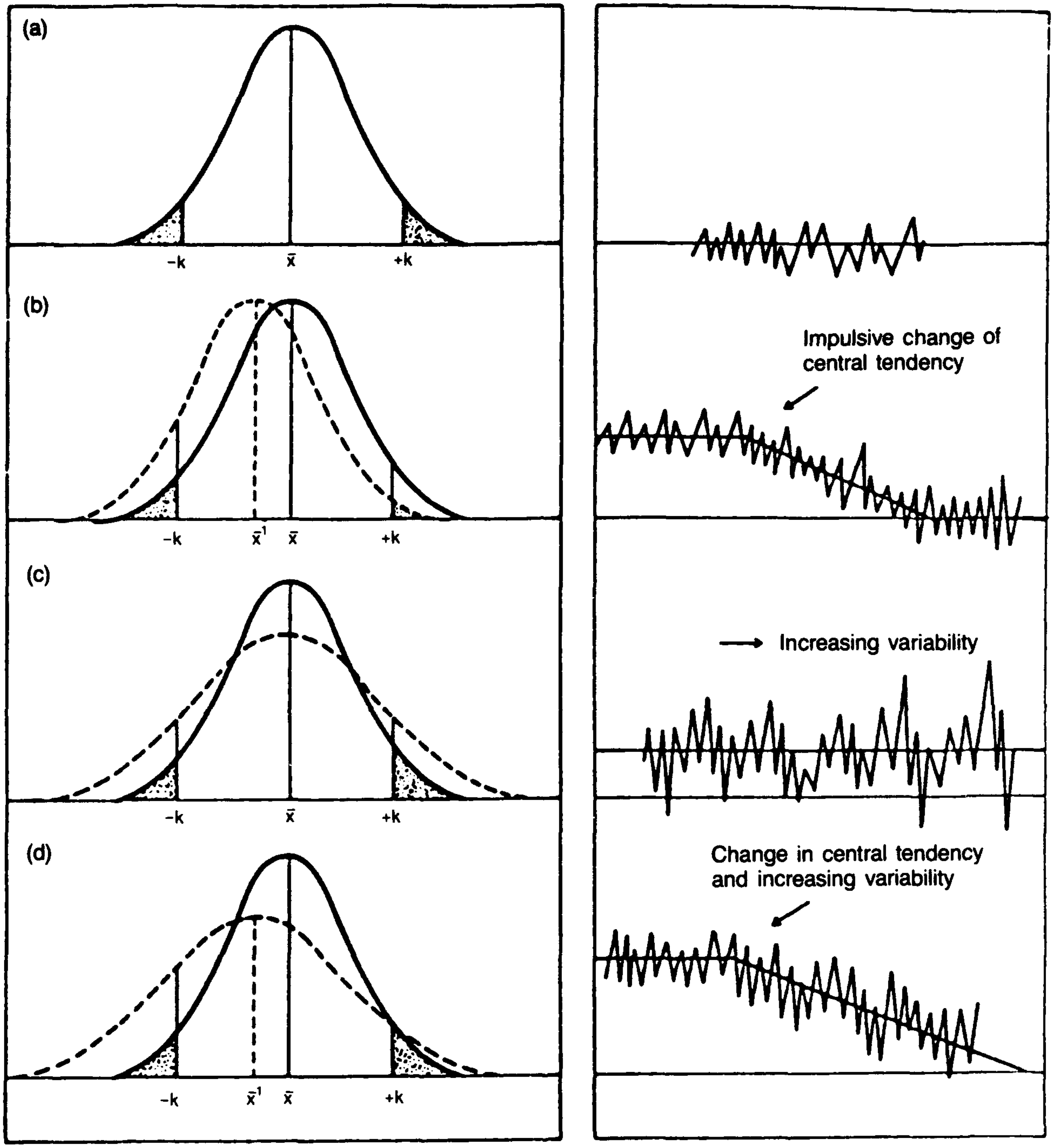

Figure 2. **Changes in probability distributions and stochastic outcomes for shifts in mean, variance, or both.**

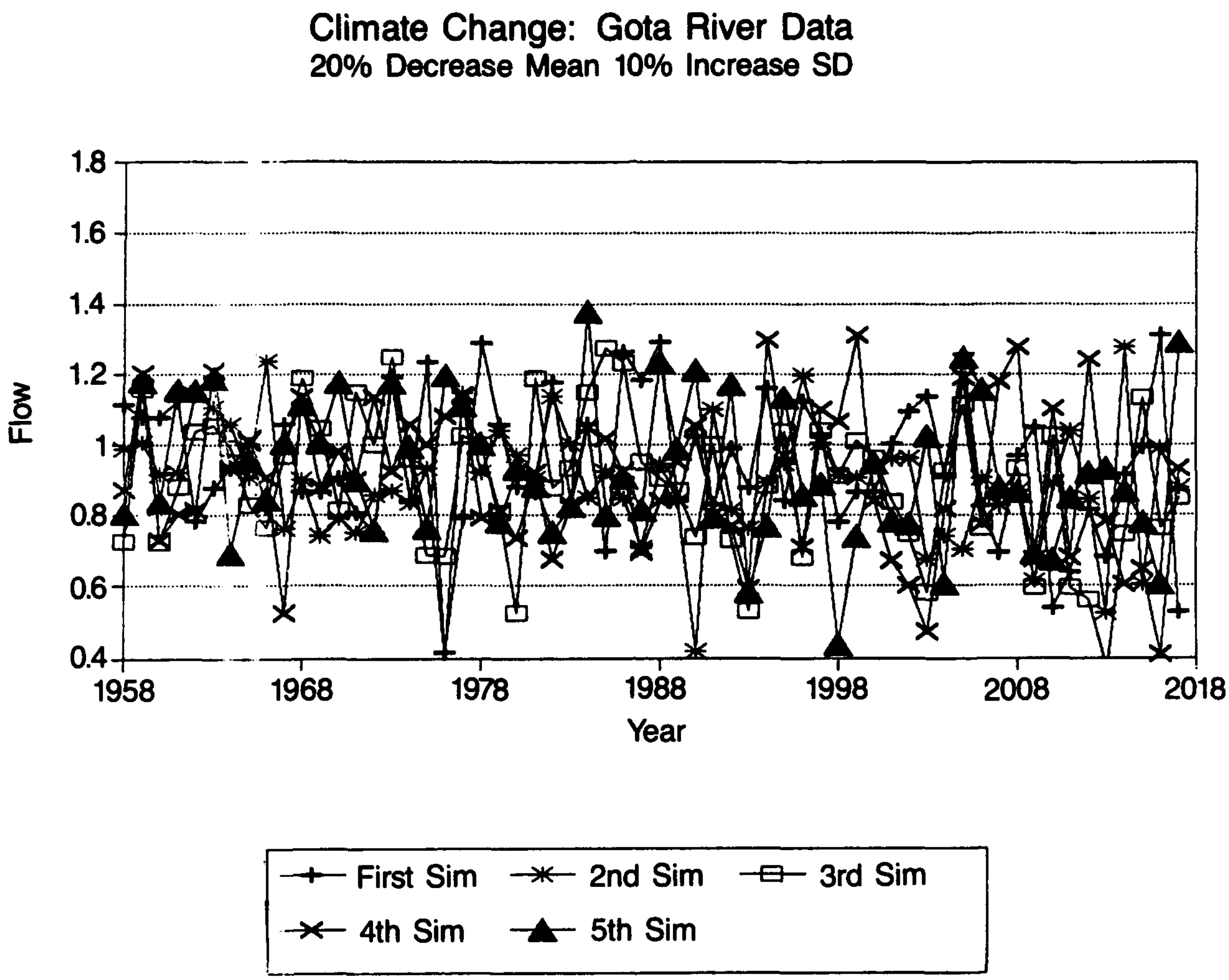

Figure 3. **Sixty-year simulation with a 20 percent decrease in the mean and a 10 percent increase in the standard deviation.**

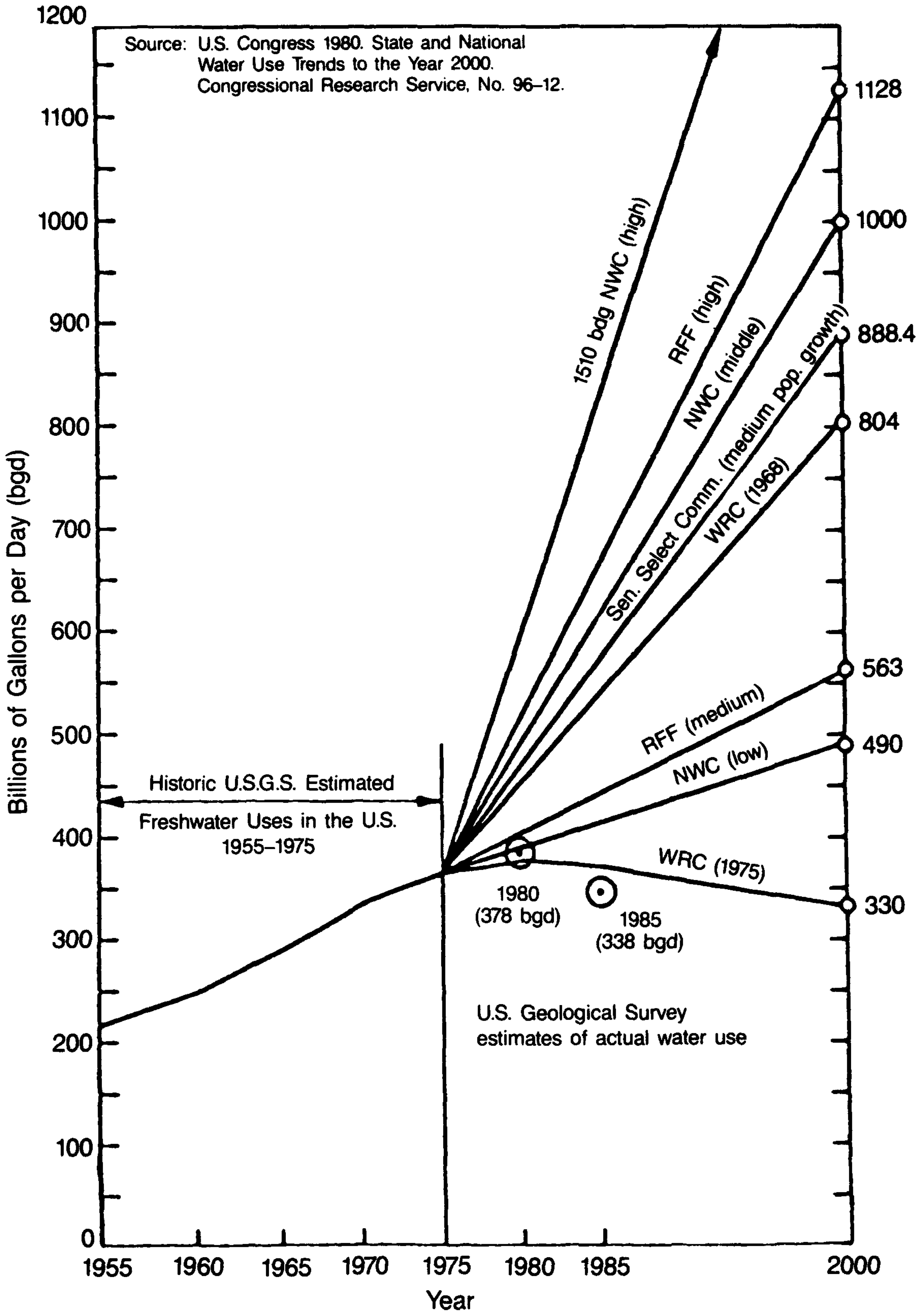

Figure 4. **Projections of fresh-water withdrawals for 1975–2000 from various sources.**

If we now take into account the problems of making long-term projections of demand for water, I believe that we have little chance to predict what happens in the distant future. For example, Figure 4 (based upon the Congressional Research Service, 1980) shows some of the problems faced by managers and planners of water resources when making predictions over relatively short time periods--and I stress that this is only for 25 years, not 100 years as most climate-change scenarios require. The figure plots projections made in 1975 for the year 2000 by four major studies of future water demands in the United States along with the best estimates that we have for actual withdrawals for 1980 and 1985. For the year 2000, projected demand ranges from a high of 1,510 bgd to a low of 330 bgd. The low figure was an almost threefold downward revision by the Water Resources Council of its own 1968 forecast. The actual 1985 usage was reported at 338 bgd, which was an 11 percent decline from 1980, and well below the greatly reduced 1975 Water Resources Council forecast.

The Potomac River case discussed briefly above shows the hazards of making errors in forecasting the demand for water, even for periods as short as 25 years into the future. Essentially, the Potomac case tells us to make flexible plans that take advantage of existing facilities.

Given the discount rates and the scale parameters, the optimal planning period is usually less than 20 years. The Schwarz results indicate that, even with very strong assumptions about climate change, the range of responses of the system are well within the range of uncertainty about the social and economic parameters, and within the range of fairly easy adaptation if required.

The California case presented the best evidence of the adaptations available in modern U.S. circumstances. While the adaptations are by no means painless, the magnitudes of the seeming "shortfall" were far beyond what could be expected under climate change scenarios. For California, I would conclude that we should not be worrying about climate change; rather, we have completely misperceived what is "normal" climate in that region and what economic activities can be realistically supported by that normal climate.

I hope that I have convinced you of my contention that even if we knew the future hydrologic parameters exactly, we would not change how we currently carry out water planning and management in the United States. This does not mean, however, that *we should not concern ourselves with climate change*. We should. What it does mean is that we should not be stampeded into taking inappropriate action. There is a growing clamor, often from scientists who should know better, for preemptive action even before we know the consequences, "because the costs of being wrong" may be catastrophic. Obviously we should keep our eyes open for the occasional catastrophe--one good catastrophe can ruin your whole day! How do we avoid the catastrophes? We do this by continuing to carry on research on the nexus of climate change and water resources, but not solely on the hydrology but also upon other parts of the aquatic ecosystem. I am concerned that the consequences of possible climate change upon stream biota and other ecosystems dependent upon water are being ignored. Research on these consequences is being neglected by a science policy that misallocates the climate research monies to large-scale climate modeling at the expense of what I think are more likely valuable areas of knowledge as guides to action. I think that this paper also demonstrates the need for more research in the areas of the adaptation of existing water resources systems to climate change. Research is needed on both the supply-side and the demand-side adaptations.

This paper demonstrates that we are far from a crisis in U.S. water resources due to climate change. It shows were the major uncertainties lie in making rational plans for water and it indicates a shift in research emphasis with regard to climate change.

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THE KNOWNS AND UNKNOWNS OF CLIMATE CHANGE: WHAT SCIENCE TELLS US

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ABSTRACT

The notion that mankind is bringing about a warming of the earth, primarily by the burning of fossil fuels, has received great popular attention lately. There is considerable apprehension that a global warming will cause some undesirable shifts of rainfall and snowfall patterns as well as a disruption of agriculture and natural ecosystems. The scientific basis for expecting such a global warming is the theory of the "greenhouse effect," which is one of the best established theories in meteorology. However, the planetary system that determines our climate, including the atmosphere, the oceans, the polar ice masses, and the biosphere, is so complex that there is some uncertainty about just how it will respond to an increase in carbon dioxide and other "greenhouse gases." An articulate minority of scientists (the "nay-sayers") have capitalized on this feeling of uncertainty to try to discredit the global warming notion--thereby encouraging an attitude of complacency. Other scientists justify the same attitude by arguing that the global warming will be good for mankind. It is important that these scientific debates be understood by our political and business leaders, since the policy implications are obviously enormous. In the following we will try to show that the arguments of the nay-sayers are generally either misleading or downright wrong.

INTRODUCTION

In discussions of the notion that mankind may be causing a global warming it is imperative to separate the undisputed facts from scientific theory. As will be explained, the situation is extremely complex, and even the facts have to be interpreted carefully. Furthermore, the theory of climate is expressed through elaborate climate models run on supercomputers, and while these computer models are the best tools we have, they are admittedly still incomplete.

To start with, there can be no denying the fact that mankind is currently burning an enormous quantity of fossil fuels (coal, petroleum, and natural gas), and that in 1990 about six billion tons of carbon in the form of carbon dioxide were released into the atmosphere from fossil fuel burning. It is therefore not surprising that the concentration of carbon dioxide in the atmosphere has been rising steadily in this century, and there is now almost 30 percent more carbon dioxide in the atmosphere than there was at the beginning of the Industrial Revolution. Not all of the industrially produced carbon dioxide has remained in the atmosphere, and in the past three decades a little less than half of each year's emissions has apparently gone into the oceans of the world. Another source of carbon dioxide from human activities is the deforestation of the tropical rain forests, which may contribute about an additional 20 percent.

So far we have been dealing with observations of the real world, and now let us introduce the greenhouse effect, a theoretical concept. Sunlight passes through the atmosphere almost unattenuated where no clouds are in the way, and this warms the surface of the earth. In order to maintain an energy balance, the surface must eliminate some of that heat, and it does so by reradiating energy in the infrared part of the spectrum--the kind of radiation that cannot be seen but can be felt, and that used to be called "heat radiation." But infrared radiation from the surface is partly absorbed by some trace gases in the atmosphere, of which water vapor, carbon dioxide, and methane are the most important. These are known collectively as "greenhouse gases." The atmosphere thus traps part of the radiation that would otherwise escape to space, and this keeps the surface and lower atmosphere warmer than it would be if there were no atmosphere. This is known as the greenhouse effect, and by adding more of those infrared-absorbing gases to the atmosphere we are enhancing the effect and warming the surface.

This theory is one of the most well-established theories in meteorology. It has been tested against observations on earth, Mars, and Venus, and it is on sound scientific ground. However, it is another matter when we try to determine how the total climate system--the atmosphere, oceans, polar ice masses, biosphere, etc., all interacting with each other--will react to a change in the heat balance. The polar regions will warm more than the tropics, and this will alter the equator-to-pole temperature difference that drives the atmospheric heat engine. This will in turn change the circulation patterns of the atmosphere and the oceans, and that will alter patterns of precipitation as well as temperature.

Our climate models, run on the fastest computers available, try to take as many of these interactions into account as possible and thereby simulate the behavior of the real climate system. They do a remarkably good job of simulating reality, but they obviously cannot duplicate the almost infinite complexity of the real system in which we live. As authoritative review of where we stand in both climate theory and observations has been published recently by the International Panel on Climate Change (IPCC, 1990), so it will not be necessary to pursue the discussion in more detail here.

The more than 200 top scientists who contributed to the IPCC report agreed that a global warming must inevitably occur as a result of the increase in the greenhouse gas concentration, and that it may be occurring already. They predicted that, if mankind continues its "business-as-usual" rate of fossil fuel burning and release of greenhouse gases, the global temperature will rise from 2°C to 5°C before the end of the 21st century. Considering the upper part of this range, Planet Earth will not have experienced such a warm climate regime for a million years or more.

This was reported to the Second World Climate Conference, held in Geneva in November 1990, and the conclusion of this conference was that international action should be taken to slow the change, assumed to be on the whole highly undesirable. The action needed was inescapable: reduce the worldwide emissions of carbon dioxide and other greenhouse gases. It is not clear how this can be achieved internationally, and in any case it will be extremely difficult and expensive.

However, all this has been greeted with skepticism by those leaders who subscribe to another school of thought; one that calls for prompt draconian actions to avert the alleged climate change. The arguments set forth are usually along the line that there is too much uncertainty in the picture that scientists are drawing of a future warmer earth, and that it may be premature to try to do anything about the situation--especially since such action might be disruptive or even harmful. Political leaders tend to defer such decisive action if they can.

Recently a number of scientists have provided ammunition for the second school of thought, either purposefully or unknowingly. These skeptics have brought forth scientific arguments that tend to discredit the notion that mankind is warming the earth--or that at least downplay its seriousness. The media have often delighted in giving considerable coverage to such pronouncements. Of course, those policy-makers who are reluctant to take action welcome the pronouncements of the nay-sayers. Let's wait and see who turns out to be right, they say. It will be better for now to do nothing.

In a recent paper (Kellogg, 1991), I have attempted to analyze a number of the statements of the skeptical nay-sayers, and this will be a summary of the various arguments. Those who desire a more substantial discussion are invited to read my paper.

A LITANY OF THE SKEPTICS

The following is a short list of the arguments that have been advanced by the nay-sayers to discredit the generally held belief in the reality and seriousness of a global warming due to human activities and the greenhouse effect:

- *The Uncertainty Principle Affects All Scientific Thinking*: Scientists are trained to be skeptical of new ideas, and tend to profess that they are uncertain about the ultimate truth of any theory. The history of science shows that we have been fooled before, just when we believed that we had a theory well established. This sense of uncertainty is particularly prevalent when we are dealing with a system as complex as that which determines our climate, and indeed there are many things about that system that we do not yet understand. We fully expect, for example, that the oceans will provide some surprises in the future. To some extent, then, the skeptics of the greenhouse theory of climate change are justified in exploiting this deep-seated feeling of uncertainty, a feeling shared by all serious scientists. However, is it fair to utterly discredit the greenhouse theory of global warming because scientists admit that there are some gaps in their knowledge? Most scientists who are actually doing research on climate would heartily disagree. The notion of a global warming is too well established now.

- *We Have Not Seen Any Global Warming Yet*: This appeal comes in two parts. First, the observed global mean temperature rise in this century of about 0.6°C is claimed by the skeptics to be "statistically insignificant," in view of the large variations in global temperature that have occurred in the past. It could be just a temporary feature of a noisy record, they maintain. However, a simple signal-to-noise analysis shows that the probability of the 90-year rise in temperature being a product of the random fluctuations is considerably less than 1 percent. The second part of this argument depends on the observation that in fact there has been virtually no observed warming trend in the continental United States, and that the North Atlantic and the North Pacific have actually grown cooler in the last two decades or so. Thus, they say, there must be something wrong with the theory. The answer is not simple, but it must be pointed out that the lower 48 states occupy less than 5 percent of the area of the world, so are not representative of the globe. And as for the northern oceans, we can see that the changes in both atmospheric and oceanic circulations can account in large part for the temporary regional cooling. After all, it would be surprising if the response to the greenhouse effect were a simple and uniform one in all parts of the world.

- *There Are Negative Feedbacks That Will Counteract the Greenhouse Effect*: Climate modelers are well aware of the fact that the complex climate system has many positive (amplifying) and negative (damping) feedback loops, and the current climate models take as many of these into account as computer speed and human ingenuity will allow. So far, however, no convincing negative feedback has been identified that has been overlooked by the modelers and that would justify ignoring the messages of the climate model experiments. It must be acknowledged, however, that the way we deal with clouds in our models is still unsatisfactory, and the oceans are certainly poorly understood. Thus, we may expect the skeptics to advance further suggestions involving clouds as a possible negative feedback mechanism that would slow the greenhouse warming. The oceans, on the other hand, are more often linked to possible positive feedbacks, though this is still a controversial topic.

- *The Observed Warming Is Due to Changes in the Sun Rather Than to the Greenhouse Effect*: Could it be that the observed global warming in this century is due to some other cause than the greenhouse effect? We cannot absolutely rule out that possibility, and a favorite surrogate has been changes in solar activity and output of radiation from the sun, which we now know is a slightly variable star. The observed 0.6°C rise could be accounted for if the so-called "solar constant" had risen by about 0.6 percent. There are two serious problems with this idea, however. First, the changes in sunspots and microwave emissions from the sun, which are our long-time indicators of solar activity, do not seem to be in step with the major global surface temperature changes--though there do appear to be important but subtle short-term changes in stratospheric circulations and temperatures that correlate well with solar activity changes. Second, now that we have more then 10 years of accurate measurements from satellites of the solar output, free from interference by our atmosphere, we can see that the changes in output over a solar cycle are far too small to account for the observed global change. Thus, it seems that adherents of this view will have to search for another surrogate for the greenhouse effect.

- *Satellite Observations Show No Global Warming in the Past 10 Years*: A NASA team of scientists and engineers has developed and flown a passive microwave radiometer on Nimbus-7 that can monitor the upward radiation by oxygen in the middle troposphere. This was announced as a new and "precise" survey of global temperature. The originally published record spans less than 10 years, however, covering most of the decade of the 1980s, and the fact that it showed considerable variations but no clear trend over this short period hardly constitutes a denial of the 90-year trend. Nevertheless, this record was greeted by a few skeptics as further evidence against the reality of a global warming.

- *The Warming Will Be Good for Us*: A third school of thought acknowledges the validity of the greenhouse theory of global warming and also points to the observed warming trend as real. However, it diverges from the consensus of the scientific community by maintaining that a global warming will generally be beneficial for humanity. Clearly, the message here is resonant with the message of the nay-sayers, since in effect it says to the policy-makers: Do not attempt to slow the emissions of greenhouse gases--let the warming proceed! This argument, including the policy conclusions, has been most forcefully advanced by the distinguished climatologist, Mikhail Budyko, and some of his colleagues in Leningrad (now called St. Petersburg again). Budyko maintains that while there may be a temporary drying trend in the centers of the temperate continents in summer, as predicted by most of the climate-model experiments, as the global warming continues and approaches 3°C to 4°C, there will generally be more rainfall, and both agriculture and natural ecosystems will prosper as never before. The evidence for this contention is the reconstruction of conditions during the late Pliocene period of 3 to 4 million years ago, when (as claimed by Budyko) it was several degrees warmer than now and no major deserts existed anywhere in the world. "This casts doubt on the expediency of carrying out very expensive actions aimed at retarding or terminating global warming during the nearest decades," he said recently in a joint paper with Y.S. Sedunov.

CONCLUSIONS

Some readers of this summary may feel that no firm conclusion can be drawn about the reality of a global warming at this time. This is, of course, in line with what the nay-sayers would like us to believe. Nevertheless, the consensus of the scientific community, as reflected in the IPCC report, is that the evidence is overwhelmingly in favor of a future global warming, and furthermore that it is probably already taking place. Even though there is still some lingering uncertainty in the notion of a future global warming and its magnitude, it would surely be unwise to pretend that it is wrong. Its implications are so grave that it cannot be ignored.

No doubt there will be further discussions of all these issues in the years to come, and probably a decade from now the evidence will be so obvious that there will be little room for skepticism. Most of my colleagues would agree with that prediction.

This water resources conference has not been directly concerned with the measures that might be taken to slow the climate change, which must involve energy policy and the use of fossil fuels. Instead, the managers of water resources are concerned primarily with how to adapt to any changing patterns of precipitation and soil moisture, assuming that there is a good likelihood that they will occur.

Unfortunately, our climate models and lessons from the past still cannot give a clear picture of those future patterns, though there is little doubt that there will be shifts. This is a situation in which the climate modelers and the water resources people will have to remain in close touch.

A final judgment as to whether the changes in store for us will in fact be beneficial or detrimental will rest to a large extent with the water resources people and those who depend on water for their survival.

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POLITICAL AND INSTITUTIONAL CONSTRAINTS OF RESPONDING TO CLIMATE CHANGE

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ABSTRACT

I will begin with a brief overview of the history of water development in California and the West, which is heavily influenced by the doctrine of appropriative water rights. In the past, planning of most major water projects was based on the worst previous dry period. Changes in weather patterns could have significant impacts on yields of water supply facilities.

The projected climate changes are well into the future and uncertain. The water planning horizon is now around 25 years with some thought out to 50 years. Changes in precipitation, both amounts and seasonal timing, are of paramount importance in water resources, but also difficult to predict. High-growth areas are generally behind in assuring reliable supplies, putting more pressure on operation of existing projects. Additional water supply and storage facilities are needed now and would provide better capability to deal with climate change. Also, we are finding that earlier projects often provided less downstream flow than is necessary to maintain historic fishery populations. There is added pressure to restore natural streamflows at the expense of established agricultural and urban uses.

Significant hydrologic impacts from climate change could be (1) a change in seasonal runoff patterns with less winter snow and less spring snowmelt runoff from mountain areas, (2) a tendency for higher evapotranspiration, (3) possible sea-level rise with more river estuary salinity intrusion and flooding during storms, and (4) an increase in flood threats. More temperature-related problems could be expected for cold-water fisheries, especially anadromous fish like salmon.

Climate change introduces new uncertainties into the water resources decision-making process. Existing institutions have some flexibility and water management changes tend to take place as public needs are redefined. But future changes need to be fair to all interests, and we do not want to rush into ambitious programs to handle future problems that may turn out to be minor.

While water managers and engineers will meet the climate-change challenge, the emphasis will always be on the shorter term problems. Global warming studies will give us some idea of possible long-range future changes so more flexibility can be built into existing water systems and future systems can be planned to accommodate changes.

INTRODUCTION

The subject of global warming and climate change is something that has not greatly influenced the planning efforts of most of us in the water resources field. This is partly due to the natural skepticism of the engineering community, but the major reason for this is that projected climate changes are well into the future and uncertain. The water planning horizon is now around 25 years with some projections as far as 50 years in the future. The most rapidly growing areas of the country are generally behind in assuring reliable supplies, which is putting more pressure on existing projects. Additional water supplies, beyond water conservation and reclamation, are needed now to meet present and future needs. This would also provide better capability to deal with climate change. The current shortfall is due to a number of factors that have caused most of the western United States and some other regions of the nation to reach or exceed the reliable supply of water. These factors include an almost total cessation of construction of new water supply facilities due to their high costs, growth-management issues, and increasingly complex environmental constraints. Environmental constraints have included recognition of the need for protection of wetlands--threatened and endangered species requirements have placed additional restrictions on proposed as well as existing projects--and a number of court decisions extending the requirements of Section 404 of the Clean Water Act and applying the public trust to water rights. Climate change, to the extent it occurs, just complicates the uncertainties that must be resolved in meeting future water needs.

No one knows for sure how the atmosphere and weather systems will react to more greenhouse gases and other climate factors. My purpose in today's presentation is not to enter the dialogue over the nature and extent of these climate changes. This is a matter of ongoing research. My discussion assumes that some future changes to the climate will occur, regardless of cause, so that some observations on the present and future impacts of climate change can be made. Obviously, the amount of temperature change and the amount and seasonal timing of precipitation changes are critical in estimating future impacts on water management options.

I will begin with a brief discussion of how natural stream runoff is allocated, how water supply projects were planned, and the immediate challenges to meeting future water needs aside from climate changes. This background is needed to understand the political and institutional effects of global warming on water resources, and how we might respond and adapt to any climate changes. There are no easy solutions to the immediate problems for meeting future needs for water. And adding climate change, based on the current limited knowledge, would simply add to the problem. Finally, climate change underscores the need for flexibility in planning and managing water resources systems.

Allocation of Water in the West

The doctrine of appropriation of water--the right to divert, store, and use water within or outside the watershed within which it originates--seems to have originated from early mining customs in the gold fields of California. Appropriative water rights are a "first in time, first in right" system whereby the first users had priority for reasonable use of natural streamflow. If there is not enough flow, users with more junior priorities must cease diverting. As flows decrease, gradually more and more junior users have to end diversions. This is in contrast to the riparian rights doctrine, which derives from the common law of England that recognizes equal rights among property owners that border on a stream to share its natural flow without regard to priority, and to use the water on riparian lands within the watershed. California recognizes both the riparian and appropriative water rights doctrines, as well as some other doctrinal bases for the diversion and use of water. Most other western states follow exclusively the doctrine of strict appropriation for surface water and groundwater.

Water rights doctrines evolved to allocate limited supplies of water among competing uses. The system--especially the doctrine of prior appropriation--was designed to distribute an inadequate supply. Climate change could alter streamflow regimes, which would increase the political conflicts between agricultural, urban, and instream uses of water.

Much of the existing water use in the western states depends on established water allocations, through individual water rights, adjudications which have quantified amounts and priorities of entire stream systems, negotiated agreements transferring water use and water rights, interstate compacts, and other institutions. Many of these have included delicately worked-out solutions designed to maximize the number of reasonable and beneficial uses that can be made of a limited supply. Any climate changes that significantly alter the quantity or timing of natural streamflow would probably require changes in these institutional arrangements and would cause substantial uncertainty over the long term. However, it should be noted that other factors contribute to uncertainty over these institutional arrangements. Water rights in many areas no longer seem to be as certain as once believed. For example, in California, the application of the public trust doctrine to Mono Lake, and the Bay-Delta proceedings will most likely reduce future water supplies from those sources. Climate change just introduces another source of uncertainty.

Water Projects

Planning for large water storage and conveyance projects is generally based on the worst historical dry period, often with some measure of delivery curtailment during the driest of years. Water delivery systems in the West have been funded (often with bonds) and operated on certain assumptions related to natural supply. Changes in future weather patterns would change not only the amount of runoff but also seasonal runoff patterns, which would significantly change yields of water supply facilities.

Current Challenges: Reductions in Available Supplies

The world today faces a number of immediate challenges in state and local planning and management of water, without regard to the possibility of future climate changes.

For many years, water supply systems in California have had such a reliable record of full deliveries that people in urban areas took water for granted. However, the situation is changing. Few new water projects been developed in the last 20 years, and rapid population growth is placing demands on existing systems that exceed their design yields. In addition, the supplies of many existing projects are being reduced by court decisions and changing conditions. The current 5-year drought has further dramatized the problem.

Water supplies throughout the country are being reduced as the result of demands for greater instream fisheries flows, restrictions to protect endangered species and wild and scenic rivers, and disputes over limiting growth. Consequently, the amount of water available for consumptive use is being reduced.

Until the last few years, water supply planning in California was based on the assumption that increases in water demands would be met by building more water supply facilities. This assumption has changed. It is now clear that facilities included in earlier long-range water plans are not compatible with newer environmental statutes protecting wild and scenic rivers, wetlands, and endangered species. Future projects that meet all of these requirements in effect today will be very costly, and in many instances cannot be authorized because of environmental constraints. One example is Two Forks Dam in Colorado, which was denied a permit by EPA. Fortunately, California has substantial surface and groundwater resources, and a very large interconnected storage and conveyance system that can move water supplies throughout the state.

Legal competition between traditional urban and agricultural uses and environmental uses has created a great deal of uncertainty in assessing the adequacy of existing water supplies. It will probably take several years for these conflicts to be resolved. This is the political and institutional context within which responses to climate changes will occur. Climate change may have the effect of further complicating resolution of many of the issues we face today, and most certainly would require changes in existing institutions.

Potential Effects of Climate Changes on Water Supplies

There may be some precedent in the history of the Hohokam Indian civilization of central Arizona. Hundreds of years ago these people built a large system of canals in what is today the Phoenix area, diverting water from the Salt River. For some reason, this entire system was abandoned approximately 600 years ago, and the Hohokam civilization disappeared. Many observers think climate change was a factor--either more floods or an extended drought made the canal diversion system too much of a burden to maintain for the technology of that day. While some may be tempted to speculate on similar dire predictions for our modern water development systems, today's technology is so different than 600 or 700 years ago that only limited parallels can be drawn.

Climate-change writers tend to focus on increasing heat and drought, but a modest increase in precipitation could offset the water losses. However, timing of potential precipitation changes is very important.

If precipitation remains essentially unchanged, the major hydrologic impacts, as we see them, are changes in seasonal runoff patterns due to warmer temperatures. This is especially significant in the western states, where precipitation is stored in the mountains in the form of snow. Other changes would be a tendency toward higher evapotranspiration (higher crop water use) due to warmer temperatures. Crop production, though, might go up due to the fertilizing effect of higher carbon dioxide concentration. On a longer time scale, possible sea-level rise could affect river delta and estuary areas with more dry-season salinity intrusion and more flooding during storms. Coastal erosion would increase, especially along low-lying shorelines. Temperature increase could result in flood threats because of general relationship where local storm intensity increases with warmer temperatures, resulting in more runoff during storms.

To illustrate an area where California is vulnerable, the Department of Water Resources staff estimates that a 3° Celsius temperature rise, if other climate factors remain the same, would reduce the April 1 snowpack area on California mountains by about half. The average spring snowmelt runoff during the April through July period would be reduced by around one-third. Average snowmelt runoff in the major supply watersheds is about 14 million acre-feet, or about 40 percent of the total estimated net statewide water use. A loss of one-third of this amount means a loss of over 4.5 million acre-feet of natural storage, whereby winter season precipitation is carried over in the form of snowpack for dry-season needs. The reduction would be over 10 percent of total in-state reservoir storage capacity. Replacement of this amount of water storage today is doubtful because of the high costs of developing storage, along with the environmental constraints and difficulty of financing large public projects.

Sacramento-San Joaquin Delta Protection

Protection of the Sacramento-San Joaquin Delta is California's most significant water issue. With more than two-thirds of the state's population dependent on diversions from the delta, its importance cannot be overstated. It will be politically difficult to construct new water facilities without guarantee that the bay-delta estuary will be protected from adverse environmental effects of these projects.

Obviously, the quality of water in the delta can also be threatened by salt water through failure of existing levees. Much of this land is peat soil and below sea level, protected by 1,100 miles of levees. Every major flood this century has caused levee problems somewhere in the delta. While a small sea-level rise may be tolerated, a major rise could cause serious flooding and disruption of water supplies to many areas of the state. A 1-foot sea-level rise (0.3 meter) could transform the 100-year high-tide peak at Antioch, a western delta location, into a 10-year event.

Flood Protection

Flood protection is not only a coastal and estuarial problem. Dams, levees, floodplain zoning, and insurance would be affected if the hydrology of the watershed is altered due to vegetative and storm-pattern changes. Across the nation a whole set of programs, including flood insurance and flood damage prevention, are built upon the once-in-100-years return frequency for flooding. What was thought to be 100-year protection may turn out to be 60- or 80-year protection. Because of existing development and environmental concerns, it would be extremely costly and difficult to provide adequate flood protection. The Sacramento urban area, where I live, can be cited as one example. A reevaluation of American River hydrology in the wake of the 1986 floods revealed that flood protection provided by the existing system was much less than previously thought. The only feasible solution appears to be new flood control storage at the proposed Auburn Dam, which is controversial and expensive. While the change in American River flood hydrology is not the result of global warming, it illustrates some of the problems that could occur as a result of significant global warming.

Protection of Fisheries

Temperature rise could also have a profound effect on fish and wildlife. On the Pacific Coast, anadromous fish like salmon often encounter water-temperature problems, especially in a dry year when reservoir levels are lower and warm water is discharged. Newer dams have temperature-control outlets that allow water to be released at various levels to regulate temperature, but retrofitting older dams that do not have temperature control facilities is very expensive. A temperature control facility at Shasta Dam (a key federal Central Valley Project reservoir operated by the Bureau of Reclamation), which would be authorized by legislation pending in Congress, is estimated to cost $50 million. Global warming may make it impossible to preserve some cold-water fish without providing artificial temperature control at other large dams that presently lack these facilities.

Conjunctive Use of Groundwater Basins

Conjunctive use of water, by recharging groundwater basins with surface water, will play an expanded role in meeting future water supply needs. Water in groundwater basins can be used in dry years as a reserve supply, if the basins are recharged in wet years. Increased storage, both in surface reservoirs and groundwater basins, could be a possible answer to increasing flexibility and adapting to climate change. However, the period of time when surplus flows for recharge are available is likely to shrink also.

Water Conservation and Increased Efficiency of Use

Later in the program, demand management will be discussed, and I would like to make a couple of observations on increasing water use efficiency. Opinion surveys over the last decade have repeatedly indicated that the public believes that water conservation should be a high priority in water management programs.

California has many programs that encourage and assist in the implementation of water conservation, both in the urban and agricultural sectors. Most urban water suppliers in California are required to adopt and implement water conservation plans, and a set of "Best Management Practices" setting conservation standards and objectives for urban water suppliers was recently developed.

Evaluation of the true water resources savings requires a look at the entire hydrologic system, including the deliberate or indirect reuse of waste water and return flow. In California, the major potential for real savings is generally in coastal urban centers where waste water discharges to the ocean. A lot of people in California say that since irrigated agriculture uses 80 percent of the water, a small increase in efficiency will yield plenty of water for new urban growth. In fact, the amount of water that can be conserved by farmers is much debated. Farmers in California point to a long record of conservation practices, such as drip irrigation, micro sprinklers, and laser land leveling. A significant temperature increase could increase the evapotranspiration demands of crops, and could offset the benefits of increased agricultural water conservation. In any event, the increasing cost of water, which encourages farmers to be more efficient, and cooperative programs between urban and agricultural agencies, will result in additional conserved agricultural water. In some cases environmental impacts may result from agricultural conservation and water salvage programs, including increasing salinity, loss of water for fish and wildlife, and an overall loss of habitat.

The Drought in California

California's drought has now lasted 5 years, and it has been the worst 5 years of record across the central part of the state. However, it has not been quite as dry as the previous 1929-1934 6-year drought in northern California. Our system of reservoirs served well during the first several years, but the continuing dry years have extracted their toll. The California State Water Project only delivered 20 percent of its urban requests this year and no water to its agricultural users. The large federal Central Valley Project curtailed supplies from 25 to 75 percent, depending on the type of contract. We ended water year 1991 on September 30 with about 60 percent of average storage in the state's major reservoirs. Precipitation over the 5-year period averaged about 75 percent of average, and runoff about half of average. To a large extent the severity of the drought has been softened for many users by large extractions of groundwater. If such droughts are symptomatic of what to expect with global warming, then the temporary increase in groundwater use would not be an option and we would probably see much less irrigated agriculture. The drought may be a better predictor of the possible impact on the natural systems in our environment.

The Role of Climate-Change Predictions in Water Planning

Existing institutions are not inflexible; changes have taken place as public needs are redefined, and the current environmental movement can be cited as evidence of this. I am optimistic that future changes will be made in a manner that is fair to all interests. Many of these changes will include a combination of future water supply strategies, including conservation programs to achieve greater efficiencies, offstream storage, conjunctive use of groundwater, voluntary water transfers, waste-water reclamation, desalting, and fish and wildlife protection and restoration programs. However, in view of the existing institutional complexities of those strategies, we should not encumber them unnecessarily with additional constraints based on uncertain projections about global warming.

In view of the high cost of implementing many of the future water supply strategies, we should be cautious about rushing into ambitious and costly programs to handle future climate-change problems until they are adequately defined. Based upon our present knowledge, there is still uncertainty about if or when these problems will materialize, and about their severity. However, water managers must be prepared to meet the climate-change challenge as ongoing research provides us with better predictions that can be relied upon in the 25- to 50-year future time frame normally used in water resources planning.

CLIMATE AND OTHER GLOBAL CHANGES AND WATER RESOURCES

Harlan L. Watson, Ph.D.

ABSTRACT

I welcome the opportunity to speak here today at the First National Conference on Climate Change and Water Resources Management. This is truly a national conference--I noted from the program that there are attendees from some 33 states, including a mix of federal, regional, state, and local water resources managers; academia; private research organizations; and private-sector firms. This is also an interdisciplinary conference that includes scientists, engineers, economists, political scientists, and policy-makers. This conference represents a great opportunity to enhance understanding of both climate change and water resources management and the relationships between them.

Perhaps the most significant of all the effects of global climate change are those related to water resources. Potential effects in the agricultural, forestry, and other sectors, although of justifiable concern, are actually derivative problems stemming from the climate-change effects on water availability. Clearly, potential changes in the quantity and quality of water, and the demand for water, are one of the most central issues in the current worldwide efforts to understand and deal with climate change. Both nationally and internationally, a reliable water supply is an essential base for social, economic, and political stability.

The issue would be troublesome enough if it were merely a matter of estimating future hydrologic conditions. However, it is also necessary to incorporate social and economic dynamics. In fact, climate change is only one of several global changes determining future natural resources use and management. Other agents of global change, such as population and economic growth and technological progress, play an even more significant role.

Population growth will inevitably increase the pressure and demands on resources of all kinds. Over the next century, the world's population is expected to increase from the current level of 5.4 billion to between 11 and 15 billion. If all else remains fixed, such an increase would increase pressures on natural resources twofold to threefold.

Economic growth can also stimulate demand even as it makes resource and environmental protection more affordable. If the world population doubles by the year 2050, and the per capita economic growth increases at 2 percent per year until then--all else being equal--the demand on any natural resource will increase about 650 percent above today's level.

Technological progress, and human adaptation in light of that progress, can, however, offset the pressures on natural resources due to population and economic growth by improving the productivity and efficiency of activities using natural resources as well as stimulate substitution of one form of natural resource for the use of another. The experience with agriculture in the United States provides the best illustration of technical progress. There has been a 14-fold increase in farm productivity per unit of labor from 1900 to 1988.

During the first assessment of the World Meteorological Organization/United Nations Environment Programme Intergovernmental Panel on Climate Change (IPCC) in 1990, scientists participating in the working group that investigated the potential impacts of climate change realized that producing an estimate of agriculture, water resources, human settlement, and other conditions in a climate that may exist 40 to 50 years in the future would be misleading at best, and unrealistic at worst, unless estimates of the social and economic conditions likely to exist in these future decades were also prepared. To acquire estimates of future water resources conditions, appropriate for planning and policy formulation, consideration must be given to the following:

- Physical changes likely to occur in the climate and hydrologic systems associated with both human-induced and nonhuman influences

- Social and economic changes not affected by climate

- Social and economic changes that occur in response to climate and that may, in turn, produce their own effect on the climate

Clearly, this poses an awesome challenge. On the one hand, the skill with which we are currently able to model present climate or predict future climates is very poor. On the other hand, the skill with which we are currently able to predict social and economic conditions years to decades in the future is perhaps worse. Obviously, attempting to focus on long-term changes in water resources is a tenuous exercise at best. However, it is important to note that the impact of climate change is, generally speaking, not in the several-hundred-percent range as is expected to result from the other major agents of global change such as population and economic growth and technological progress. It is considerations such as these that led Jesse H. Ausubel of Rockefeller University to ask in the April 25, 1991, issue of *Nature*, perhaps only partly tongue-in-cheek, "Does climate still matter?"

This is not to say we are incapable of developing some important insights and understanding, however. Significantly, the IPCC report noted that, on a worldwide basis, very little has been documented regarding the sensitivity and vulnerability of water resources to present-day climate variability--and there is tremendous present-day variability. As Gary Hester of the California Department of Water Resources notes in the abstract of the talk that he will give here later: "During the past 10 years, hydrologic conditions in California have included the greatest seasonal snowpack, the wettest consecutive 2 years, a flood of record, and most recently, the driest 5-year period (still in progress) in nearly 60 years."

In addition to citing the need for identifying basin sensitivities, the IPCC also noted the need for developing methods that permit the climate data and information currently available to be used more meaningfully in assessing water resources response.

The one point that will undoubtedly be reiterated time and time again during the next several days is that changes in climate and water resources are extremely uncertain. Such uncertainty, both near term and long term, demands that those responsible for managing and establishing policy related to water resources carefully monitor new information and techniques and make use of them as appropriate.

With the U.S. Global Change Research Program (USGCRP), the federal government has undertaken a significant effort to reduce scientific uncertainties. The program is a government-wide research activity, coordinated by the President's Office of Science and Technology Policy, involving some 20 departments, agencies, and offices of the federal government--and 7 of the 9 bureaus of the Department of the Interior. Funding for the current fiscal year (1992) will exceed $1 billion, and an enormous effort is being made to understand how climate and water resources influence each other. Many of these activities, including some results, will be described during the course of this conference. I hope that those of you who are water resources managers will gain new insights about how to address the issue of climate uncertainty.

I also hope that all of you will go home with an increased awareness of the current efforts to improve climate models and their linkage with watershed models. Some of the techniques and approaches that will be discussed here have a direct applicability to water resources management--with or without climate change. I believe that the attention being focused on water resources management in light of climate change will add to our ability to be good stewards of our water resources. I wish you great success in this important conference.

II. Regional Sensitivity to Climate Change

REGIONAL SENSITIVITY TO GLOBAL CLIMATE CHANGE: WESTERN REGION

Stanley G. Coloff, Chairperson
Ann Ball, Rapporteur

This summary provides a synopsis of the session and focuses on the discussion between the presenter and participants and among the participants. As always, there were more questions than answers.

The session included five speakers whose presentations encompassed assessing the regional sensitivity of specific river basins to global climate change, describing attempts to determine what the historical data is telling us, and evaluating possible institutional and management responses to such changes. In this session John Dracup studied long-term trends in hydrometeorological data in California (The Effect of Climate Change on California's Water Supplies); Charles DuMars examined the capacity of the legal institutions to respond effectively to change (Institutional and Legal Responses to Global Climate Change in the Rio Grande Basin); Linda Nash discussed the results of modeling the sensitivity of long-term temperature and precipitation changes in the Colorado River basin (The Implications of Climate Change for Water Resources in the Colorado River Basin); Dennis Lettenmaier focused on the Pacific Northwest response (Sensitivity of Pacific Northwest Water Resources to Global Warming); and Ronald Schuster presented various approaches that water managers may take in response to potential global climate change (Climate Change and Water Resources Management: Now That We Know the Issues--What Can We Do?).

The Effect of Climate Change on California's Water Supplies

Can historical data be used to ascertain long-term trends in streamflow runoff? If so, can these trends be used to signal global warming? Studies conducted by the California Department of Water Resources (DWR) suggest a long-term decreasing trend in California's April-to-July runoff, yet other investigators have determined that there is no evidence to support a hypothesis of any significant trend in the hydrometeorological time series data. In California, interannual streamflow runoff varies considerably. Is this variability natural or a function of global climate change? The data are conflicting and do not allow a definitive conclusion.

Institutional and Legal Responses to Global Climate Change in the Rio Grande Basin

Flexibility of existing legal institutions in responding to water supply changes resulting from climate change was seriously questioned. These institutions are based on the assumptions of continued water supply and predictable variability in runoff. These assumptions are no longer valid; consequently, Mr. DuMars recommends that the laws be rewritten to allow greater flexibility in responding to changing conditions through market concepts. Clarification of ownership rights, refinement of public interest criteria, development of international groundwater treaties, and the reevaluation of existing permit procedures need to be addressed. Without such changes, Mr. DuMars predicts that the result of climate change would be an economic and legal race to acquire water rights and secure institutional leverage. It was also suggested that "water grabbing" in the West will begin with or without global climate change and that action should be taken anyway.

The Implications of Climate Change for Water Resources in the Colorado River Basin

A conceptual hydrologic model and a reservoir simulation model were used to study the sensitivity of the surface runoff and water supply to regional changes in temperature and precipitation. Variations in mean annual runoff of 30 percent due to climate change are possible. The Colorado River system, however, demonstrates much flexibility in response to these changes, largely due to its vast storage. Distinguishing natural variability from actual climate change arose as a major issue. Also, there was a great deal of discussion concerning the use of hydrologic models calibrated under one climate condition in another scenario. Concern was expressed over putting too much emphasis on scenario analysis. Do these simulations reflect reality? The argument was advanced that a scenario need not be true to be useful.

Sensitivity of Pacific Northwest Water Resources to Global Warming

How much of the shift in streamflow resulting from climate change can be recaptured through reservoir management? The sensitivity to climate change in Washington's Yakima River basin was assessed. Changes in runoff resulting from increases of 2°C and 4°C were modeled using a deterministic snow accumulation and ablation model. The effect of the altered hydrology was tested on hypothetical multiple-purpose reservoirs of size 0.25 and 0.5 of the mean annual flow. The results showed that water supply reliability would be decreased, but that hydropower generation could be increased substantially through system optimization.

Climate Change and Water Resources Management: Now That We Know the Issues--What Can We Do?

Various management approaches taken in response to global climate change were analyzed in this presentation. Possible approaches included mitigation, adaptation, continued research and development, or maintaining the status quo. The policy questions, risks, and tradeoffs that need to be considered for each of these approaches were discussed.

During the wrap-up session there was considerable discussion about the need for improved climate models. Some participants were of the opinion that major improvements in climate modeling were being made and that these improvements would increase predictive and analytical capabilities. An opinion was also expressed that rather than continuing to focus on the refinement of models, more effort and attention should be focused on dealing with the difficult political issues in water resources management. A further view was expressed that certain management and legal actions need to take place in managing water resources regardless of the uncertainty associated with the potential impacts of global climate on water resources in the western United States.

INSTITUTIONAL AND LEGAL RESPONSES TO GLOBAL CLIMATE CHANGE IN THE UPPER RIO GRANDE BASIN

Charles T. DuMars
Professor of Law
University of New Mexico Law School

ABSTRACT
MARGINALITY IN THE RIO GRANDE BASIN[1]

The Rio Grande basin will be subject to great institutional and legal change in response to global changes in climate because it is on the "margin" in many senses of the term. Marginality can be spatial, economic, or social (Parry, 1985). Geographical marginality represents a transition zone beyond which some activity or species cannot exist; for example, an ecotone in ecology, or temperature as a climatically limiting factor for certain crops. Economic marginality describes an activity that is on the edge of profitability. Social marginality refers to groups that are at risk of losing their cultural identity and/or traditional resource base should conditions change and they are no longer able to maintain their livelihood. The hypothesis usually employed is that climate change will manifest itself, first and to the greatest degree, at these margins. One should therefore focus on these for the impacts and the evidence of change. The Rio Grande basin is full of such margins.

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[1] All of the descriptive data in this paper is taken verbatim from a proposal to EPA written by the author and other members of the University of New Mexico (UNM) team, the Rio Grande Basin Interdisciplinary Group (RIGBIG). The group was formed in 1990 to develop a long-range plan for climate-change research in the Rio Grande drainage basin. The group was characterized by diversity of expertise: systems ecology, law, civil engineering, resource economics, geography, sociology, psychology, and business management. Although group members represented widely differing areas of specialization, they were drawn together by a shared interest in understanding how geologic conditions, climate regimes, legal institutions, demographic and economic patterns, political policy, and cultural values interact in determining the allocation of water resources in a semi-arid region such as the Rio Grande basin. A grant awarded through the University of New Mexico Faculty Scholars Program supported development of the team. Most of its members had worked together before as part of a network of UNM faculty whose collaboration in the development of research, education, and public service initiatives is coordinated by the Natural Resources Center. The NRC is an interdisciplinary association of UNM faculty and professional staff who share an interest in joint projects focused on natural resources and environmental issues. NRC associates include representatives from the School of Law, the School of Architecture and Community Planning, the Division of Public Administration, the Native American Studies Center, the Latin American Studies Center, the Southwest Hispanic Research Institute, and the Departments of Biology, Civil Engineering, Geology, Geography, Economics, and Political Science. The team members were James T. Gosz, Biology; Charles T. DuMars, Law; Michelle Minnis, Public Administration; Steve Thompson, Geography; Bruce Thomson, Engineering; and Chris Nunn, Economics. Professor DuMars considers the work with this group the most rewarding of his academic life and any value in the way ideas are expressed or in substance that might be found in this paper should be considered the product of the collective effort of this group.

Physical Factors

The first, and perhaps most obvious, physical factor for evaluating water by a drainage basin is the hydrologic unity of the system (see Table 1). Water, sediment, and chemicals all drain to a common outlet and activities in one part of the basin affect activities in another. For example, over-grazing upstream can lead to increased erosion, which might show up downstream as aggradation of the streambed and siltation of reservoirs. The drainage basin has long been recognized, in principle, as a desirable unit for managing water and related land resources, though meaningful implementation has largely proven elusive (North et al., 1981).

Precipitation variability throughout the basin is the second physical factor. As seen on Figure 1, one of the isolines of maximum precipitation variability in North America runs through the Rio Grande basin. This threshold axis of variability may prove useful as a regional indicator of climate change.

Ecological patterns in the basin demonstrate a similar conjunction of margins. Four major biomes come together within the basin (see Figure 2). These ecotonal edges may also prove useful as indicators of the direction and magnitude of change. It was these unique patterns that were largely responsible for the establishment of the Sevilleta Long Term Ecological Research (LTER) site south of Albuquerque.

The last physical factor is the regional scale of the basin. While the issue is global, regional-scale effects will determine social and economic impacts and policy response. The regional scale represents a common level being approached from both directions. Global modelers recognize the need to scale down to provide policy-relevant information, while at the same time local government officials are often faced with the dilemma that environmental issues transcend local boundaries. An important psychological factor affecting personal response and decision-making is the sense that one is part of a larger system--that one's actions have implications for the larger system.

Social Factors

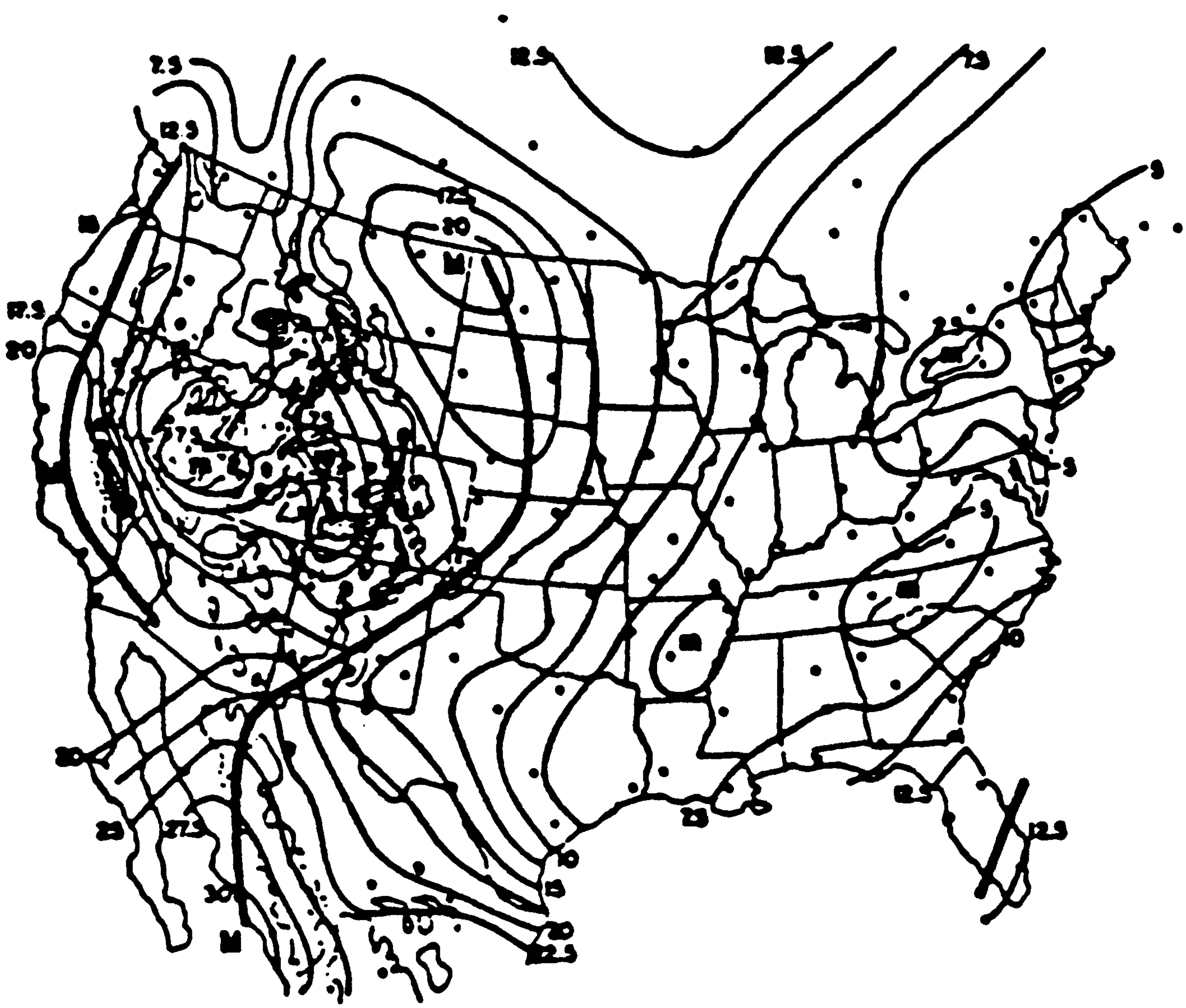
In the Rio Grande water resources region, total water consumption exceeds naturally available supply (Miller, 1989). The difference is made up through inter-basin diversions and groundwater mining. The basin is extremely vulnerable to any change that would further decrease available supply. Very little work has been done on possible impacts to water supply in this region; however, the study by Revelle and Waggoner (1983) demonstrated that a modest scenario of increasing average temperature by 2°C and reducing average annual

Table 1

Attributes of the Rio Grande Basin

Physical	Social
Hydrologic unity	Water use exceeds availability
Climate variability	Culturally significant agriculture
Ecological patterns	Unique international boundary
Regional scale	Cultural history
	Institutional structures
	Sense of community
	Existing resources

Source: Proposal submitted to EPA March 1990, "Potential Impacts of Climate Change on the Rio Grande Basin," by Sandia National Laboratories, University of New Mexico Rio Grande Basin Interdisciplinary Group.



Source: Proposal submitted to EPA March, 1990, "Potential Impacts of Climate Change on Rio Grande Basin," by Sandia National Laboratories, the University of New Mexico Rio Grande Basin Interdisciplinary Group.

Figure 1. **Relative annual range of precipitation in percent of annual precipitation. Heavy lines: maximum axes, M = maximum, m = minimum.**

Source: Proposal submitted to EPA March, 1990, "Potential Impacts of Climate Change on Rio Grande Basin," by Sandia National Laboratories, the University of New Mexico Rio Grande Basin Interdisciplinary Group.

Figure 2. **Generalized pattern of major vegetation associations in New Mexico.**

precipitation by 10 percent could potentially reduce runoff by 76 percent. This was the largest percentage reduction for any basin in the United States. Water consumption in the Rio Grande basin is primarily for urban, agricultural, and recreational uses, with some hydroelectric power generation and some water used for cooling. A significant fraction of water used is pumped groundwater. The city of Albuquerque, for example, depends completely on groundwater for domestic use. Changing climate could have important effects on the amount of energy used for pumping.

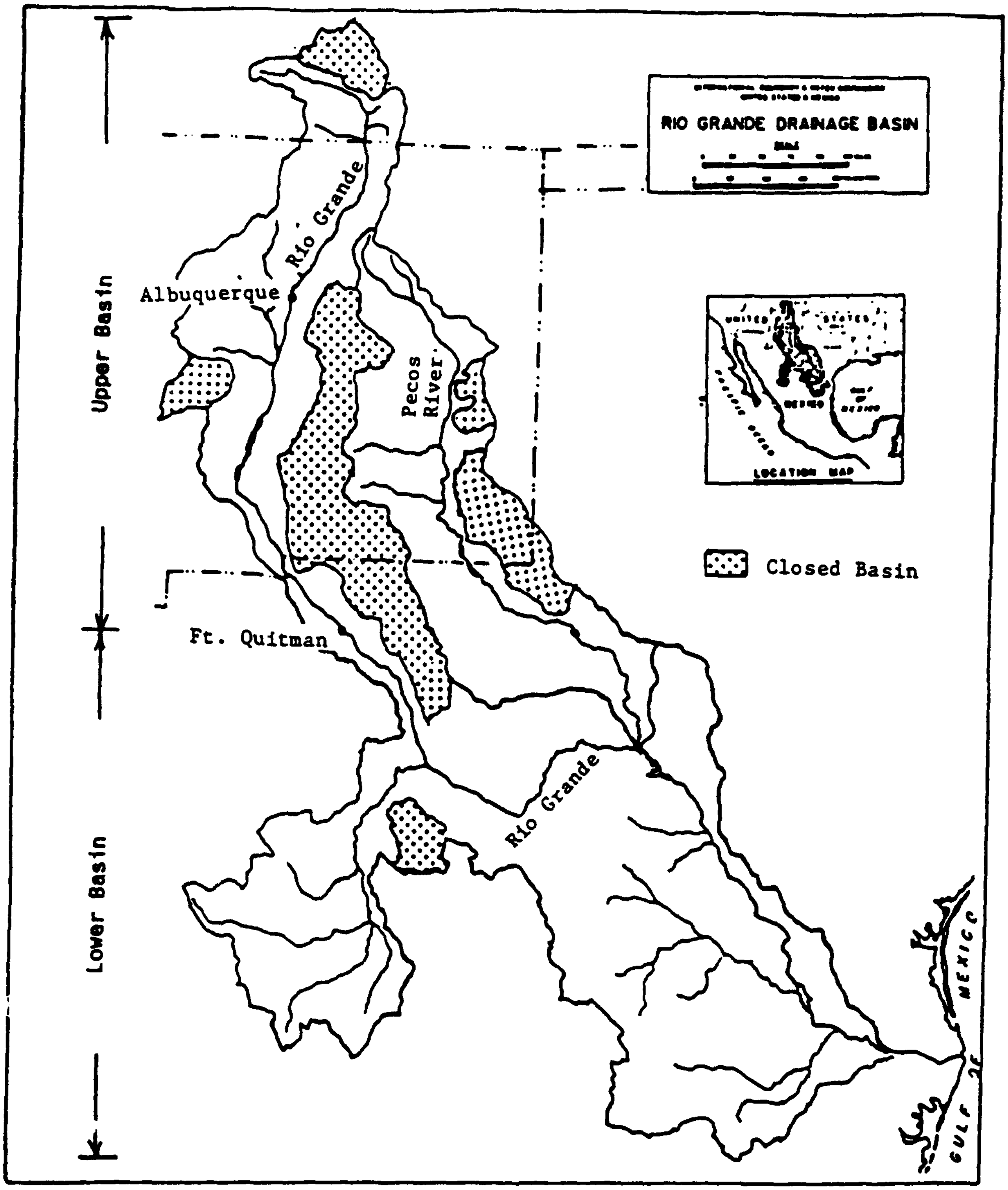
The basin (see Figure 3) has both "commercial agriculture" and what will be called "culturally significant marginal agriculture." The middle valley of the Rio Grande has one of the longest histories of continuous cultivation in the United States. In the northern basin in New Mexico, Native American (Pueblo Indian) and Hispanic (acequia) agriculture dominates. The acequia is a community ditch for delivering irrigation water. Around the community ditch have developed not just farms but also a sense of community and a way of life based on marginal irrigation agriculture. While this does not represent an important economic sector from the national or international perspective, it is important to the state and the region, especially for its cultural value. The same can be said for the Pueblo Indians, with the added dimension that their water rights are being negotiated and guaranteed under federal law (DuMars et al., 1984). This type of marginal or subsistence agriculture is characteristic of much of the world.

The Rio Grande forms the international boundary with Mexico, below El Paso, Texas. Division of the water between the United States and Mexico is spelled out in two treaties. In the United States, the water is divided between the three states of Colorado, New Mexico, and Texas by the interstate Rio Grande Compact. Thus, changes in water supply have an important international dimension. The Rio Grande has special significance as a boundary--it is the only river in the world that separates a developed industrialized nation from a developing third-world country. House (1982) denotes that character as follows:

> Along its entire length, the U.S.-Mexican boundary is one of the most remarkable and abrupt culture contact-faces in the world, between the most affluent and developed country and one [in] the midstream of development.... Nowhere else in the world are there such steep economic and social gradients across an international border. By comparison, the U.S.-Canadian boundary is extremely permeable and, "has a weak or nonexistent Border culture" (Stoddard, 1980). Perhaps the boundary between Israel and the Arab lands offers the closest parallel, but it is, quite differently, a fortified, warlike zone.....

Climate change in this region raises very important issues in international development and equity. The treaties and compacts regulating the use of water in the basin are examples of existing institutions that are already in place and focus on the Rio Grande basin as a region. Other institutional structures exist that focus on the basin; such as water quantity and quality data collection by the U.S. Geological Survey (USGS).

As mentioned above, the Rio Grande has a long history of human occupancy. When Antonio Espejo entered the region in 1539, he found the Native American Indians irrigating approximately 10,000 hectares (25,000 acres) along the river (Burkeholder, 1928). The Spanish proceeded to overlay their irrigation-based culture (the acequia system) during the 17th and 18th centuries. Anglo-Americans entered the region in the 1800s and brought with them the concept of water as private property and large-scale commercial agriculture. The basin (see Figure 3) has a rich history of cultural evolution, development, and integration. This has given rise to a sense of place and of community. A real sense exists that one lives in the "Rio Grande basin" and that this is a place rich in tradition and history. The importance of this concept was alluded to before when discussing the context that seems to be required for individuals to make environmentally conscientious decisions. This is important when addressing the questions of how to respond to climate change.



Source: Proposal submitted to EPA March, 1990, "Potential Impacts of Climate Change on Rio Grande Basin," by Sandia National Laboratories, the University of New Mexico Rio Grande Basin Interdisciplinary Group.

Figure 3. **The Rio Grande basin.**

DESCRIPTION OF THE BASIN

Land Area and Population

The Rio Grande is a long river; next to the Missouri-Mississippi system, it is the longest in the United States (Horgan, 1984). In its 1,855-mile (3,033 km) run from south-central Colorado to the Gulf of Mexico, the Rio Grande drains 355,500 square miles (920,389 square km), over half of which are located in Mexico. The basin's total land area is equal in size to 11 percent of the continental United States or 44 percent of Mexico. The area includes, on the U.S. side, portions of the states of Colorado, New Mexico, and Texas, and, on the Mexican side, portions of the provinces of Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas (Eaton and Anderson, 1987).

More than 3.5 million people reside within the Rio Grande basin. Population is heavily concentrated in the metropolitan areas of Albuquerque, New Mexico (pop. 500,000), and El Paso, Texas-Ciudad Juarez, Chihuahua (pop. 1 million), as well as in four sister cities near the river's mouth in the Gulf of Mexico--Brownsville and McAllen, Texas, and Reynosa and Matamoros, Tamaulipas (combined pop. 1 million)(Eaton and Anderson, 1987). Expanding rapidly over the last several decades, these large cities and a handful of the basin's smaller municipalities have encroached on the position of dominance in water use historically held by agricultural producers.

Urban growth is likely to continue into the next century (Williams, 1986; Eaton and Anderson, 1987), particularly along the Texas-Mexico border. Population in the border region, 2.7 million in 1980, is projected to increase by half, if not to double, by the year 2000 (Eaton and Anderson, 1987).

Cultural and economic differences among the people who depend on the Rio Grande, although perhaps sharpest in the border vicinity, are evident throughout the basin and add to the complexity of managing the river and its tributaries. Related management-complicating social factors include (1) the obligation to observe longstanding agreements about how the Rio Grande's annual flow will be apportioned among the three states and the two countries that share its waters, (2) the existence of diverse water allocation and water quality protection laws within the various jurisdictional "reaches" of the river, and (3) the pressure to adapt institutional arrangements to changes in water use demands resulting from changes in the number, distribution, and needs of the basin's residents.

The Course and Major Tributaries of the Rio Grande

The Rio Grande arises 12,000 feet above sea level, east of the Continental Divide, in the San Juan range of the southern Colorado Rockies. Descending to the southeast, the headstream is fed by several tributary creeks and the Conejos River as it flows into and through the San Luis Valley. Here, flanked by the Sangre de Cristo range, the river turns more directly south and enters New Mexico through a steep gorge. The gorge is a prominent feature of the Rio Grande Rift, a topographic depression that runs from Mexico to northern Colorado at the interface of two geologic zones, a seismologically active zone to the west and a relatively stable zone to the east (Williams, 1986; Chronic, 1987). The rift bisects New Mexico north to south and is occupied by the river over most of its course through a series of sub-basins in the northern and central parts of the state. Several tributaries--principally the Rio Chama, the Rio Puerco, and the Rio Salado--merge with the Rio Grande as it passes these basins and continues south, crossing into Texas 23 miles north of El Paso.

At El Paso, 8,000 feet below the elevation at its source, the river has completed roughly one-third of its journey to the sea. For the remaining two-thirds of its course, the Rio Grande defines the U.S.-Mexico boundary and is alternatively known by its Mexican name, Rio Bravo. Weakened by upstream diversions and accumulated silt, the river's current slows to a crawl in the flat, desert reach southeast of El Paso and is little more than a trickle for over 200 miles beyond Fort Quitman (Eaton and Anderson, 1987), the place that by international agreement demarcates upper and lower Rio Grande basins. Although Mexico and Texas share equally the waters of the lower basin, below Fort Quitman three-quarters of the supply comes from Mexican tributaries (Eaton and Anderson, 1987).

Climate and Vegetation

The Rio Grande traverses a variety of environments and terrain. In the north, where the upper basin is bordered on the east by the southern Rocky Mountains, precipitation exceeds 50 inches (130 cm) per year in the highest elevations and comes primarily as snowfall during the winter. Moving down the valley, both in latitude and elevation, precipitation decreases so that the climate is predominantly arid and semi-arid. The annual precipitation at Albuquerque averages only 8 inches (20 cm). Precipitation in the middle basin takes on a more bimodal annual distribution, with frontal precipitation in winter and summer precipitation coming as afternoon thunderstorms (Mueller, 1975).

Groundwater Aquifers

Vast aquifers underlie the surface watersheds of the Rio Grande basin and are the primary source of supply for most towns and cities along the river. These aquifers are hydrologically linked to the river, serve as recharge sources to it, and by law in New Mexico at least, are considered an extension of it. The State Engineer of New Mexico allows new groundwater development in the basin "provided the immediate and all potential effects on the flow of the Rio Grande are offset by the eventual retirement of usage under existing [surface] rights" (New Mexico Water Resources Research Institute, 1988, p. 85). Underground aquifers are significant not only because of the volume of potentially usable water they contain but also because of their vulnerability to pollution. Common sources of pollution include industrial waste water, municipal sewage, oil-field brines, and drainage from mines and farms (Williams, 1986). The decontamination of polluted groundwater is technologically more complicated and considerably more expensive than the decontamination of surface water.

Groundwater stores in the upper basin underlie an area of approximately 26,000 square miles--the same area as the surface drainage system above Elephant Butte Reservoir. Below Elephant Butte Dam, the Mesilla and Hueco basins are major aquifers (New Mexico Water Resources Research Institute, 1988; Eaton and Anderson, 1987). Wells in the Mesilla and Hueco basins are used extensively for agricultural and municipal purposes in southern New Mexico's Mesilla Valley and are the major groundwater sources in the El Paso-Ciudad Juarez area. The latter twin cities currently withdraw groundwater at the highest rate anywhere in the lower Rio Grande basin (Eaton and Anderson, 1987). There are also groundwater aquifers in the lower basin, but these are not discussed in this paper.

LEGAL INSTITUTIONS AFFECTED BY GLOBAL CLIMATE CHANGE

While the laws of nature are complex in the context of global climate change and water supply impacts, the laws of man, as reflected in the legal regime of the Rio Grande basin, are no less a challenge. These laws are a prototypical example of Justice Holmes "seamless web" of international, federal, state, and local laws. While they are complex and unique, they are much like the world legal regimes for water allocation in microcosm. They allocate water between peoples of different ethnic origins, between nations, and among states, and they attempt to balance water needs for economic development against needs for environmental protection and specialized species.

The Mexican Water Treaties of 1906 and 1944, Minute 242, and the International Boundary and Water Commission

The first level of legal constraint on the distribution of water in the Rio Grande basin is found in the Mexican Water Treaties of 1906 and 1944. The 1906 treaty obligates all of the states in the Rio Grande basin above Fort Quitman, Texas, to deliver 60,000 acre-feet of water a year for use in Mexico. Below Fort Quitman, the Rio Grande is divided by the Mexican Water Treaty of 1944, which also apportions the mainstem of the Colorado River. These allocations of water between the two countries are obligations of all the states and exist irrespective of state law.

Global climate change would raise serious questions as to how the states might respond to meet their commitment to Mexico and how Mexico might respond to uphold her responsibility under the fundamental international superstructure established by these treaties. Under international law, the differences in economic circumstances between the two countries raise fascinating and difficult legal issues that complicate any possible water allocation scenarios in times of shortage.

While the Mexican Water Treaty of 1944, on its face, does not include a quality component, Minute 242 has read one into the treaty. It authorizes the International Boundary and Water Commission (the international entity implementing the treaty) to prescribe standards for water quality. This entity has successfully required the United States to comply with maxima on salinity in water delivered in the Colorado River to Mexico. There is no reason to assume similar requirements would not be required on the Rio Grande if water supply change reduces water quality in that river as a result of global climate change.

Federal Reserved Water Rights for Indian Tribes, Wilderness Water Rights, Endangered Species Act, and Clean Water Act Wetlands Protection

A second and equally important layer of federal laws that would immediately be impacted by water supply change would be those establishing Federal Reserved Water Rights for Indian Tribes. The Rio Grande, from the Colorado border to Elephant Butte Reservoir, passes through numerous federal Indian reservations that predate the Treaty of Guadalupe Hidalgo in 1848. These Indian pueblos hold water rights reserved under federal law and treaties, which are not controlled by either interstate compacts or by state law. The extent of these rights remains unquantified, but their potential demand could far exceed water supplies currently used by non-Indians in the region (DuMars et al., 1984). In addition to these federal reserved rights, federal law provides protection for certain stretches of the river that have been designated as wild and scenic rivers or that may flow through areas designated as wilderness. A great deal of uncertainty exists about the extent of these rights; however, should any reach of the Rio Grande pass through these areas, many would argue that the minimum flows necessary to sustain the natural condition must be maintained as a matter of federal law. In addition, federal laws provide extensive protection for endangered species such as the whooping crane, which winters in the Rio Grande. Federal laws also prohibit the destruction of existing wetlands habitat. All of these federal laws will play a significant role in allocating water resources should global climate change cause a fundamental change in water supply in the basin.

The Rio Grande Compact, the Reclamation Act of 1902, and the San Juan-Chama Project

The entire reach of the Rio Grande to Elephant Butte Reservoir is allocated by the Rio Grande Compact. This interstate compact, approved by Congress, is a federal law that supersedes state law. It imposes delivery obligations on Colorado to New Mexico and on New Mexico to Texas. The exact amount of water delivered varies directly with streamflow. Thus, any climate change will directly affect the operation of this compact. Not only will water supply changes affect state obligations under the compact, they will also affect reservoir storage under the Reclamation Act of 1902, as amended. This law and its implementing general regulations control reservoir levels throughout the river. Above Elephant Butte Reservoir, accounting standards are adopted for storage in the four major New Mexico reservoirs in the basin. Any change in flows will cause changes in storage amounts and a complete recalculation of reservoir losses through evaporation and the criteria for upper basin storage. The legal implications of such changes can be extreme.

The Reclamation Act of 1902 is implicated in another way. This law regulates the use of water in the major irrigation and conservancy districts along the river. These powerful institutions allocate the water among the members of the farming community. The ability to shift water to other uses becomes affected when the policies behind the Reclamation Act conflict with alternative urban uses. The act contains three requirements that might become significant. The first prohibits the use of reclamation water for nonirrigation purposes, the second requires that reclamation water be used only within the confines of the district and, the third specifies a maximum on the number of acres any one person may irrigate, as reflected in the Reclamation Reform Act. These federal policies would all be affected by a basic change in water supply.

Finally, over 100,000 acre-feet of water are imported into the Rio Grande basin every year from the Colorado River system. A network of tunnels takes water from tributaries of the San Juan River and empties it into the Rio Chama, which ultimately flows into the mainstem of the Rio Grande. The Boulder Canyon Project Act and the San Juan/Chama Diversion Act regulate the flow of this water. It is allocated under these federal laws through contracts with the Bureau of Reclamation. Its availability for use under federal reclamation law and the interpretation of these contracts will become critical legal issues if fundamental water supply changes occur in the Rio Grande basin.

Colorado, New Mexico, Texas, and Mexican Water Law

While Colorado, New Mexico, Texas, and Mexico share the same river, they operate under different legal regimes with respect to allocation of intra-state water. Colorado and New Mexico both regulate groundwater and control the impacts of its extraction on the Rio Grande. Texas follows the rule of capture and does not vigorously regulate the groundwater resource. Mexico has nationalized all water resources in Article 27 of its Constitution of 1917 and regulates the drilling of wells.

The surface water rules of Colorado and New Mexico are similar in that they follow the rule of prior appropriation, such that the most senior rights on the river are met first. Texas follows a modified version of this rule and Mexico recognizes priorities to some degree, but exercises much more discretionary control over the resource. All of the states in the basin and Mexico have water laws that protect water quality. The following laws and institutions would also be directly affected by a decrease in water supply due to global climate change:

1. *The federal Resource Conservation and Recovery Act (RCRA).* This law directly regulates the cleanup of various existing pollutants and assigns responsibility among owners of land containing such sites.

2. *The federal Clean Water Act.* This law is relevant in many respects. First, it directly controls the ability of institutions to impact "wetlands" when they are realigning channels, pumping from wells, or otherwise working in the water conservation area in a way that affects existing waterfowl and other species of animal and plant life. In addition, there is a critical question concerning the extent to which non-point-source pollution from agriculture or timber runoff could be regulated in the event of global climate change under the act as it is currently written.

3. *The federal Safe Drinking Water Act.* Among other things, this act promotes and regulates the implementation of state well-head protection plans for domestic wells. It would be directly implicated by increased groundwater pumping or by increased groundwater pollution that may affect wells in the area.

4. *State water quality laws.* States have in the past taken the lead in developing lists of substances that cannot be introduced into the states' water supplies. They have begun action to designate certain areas as "sole sources" for domestic water and have become increasingly more active in the debate over adopting nondegradation standards for certain streams and groundwater sources. These state laws, in the full reach of the river system, would have to be changed to accommodate newly perceived threats to water supply as a result of global climate change.

5. *Mexican water quality laws and the International Boundary and Water Commission.* In Mexico, water law is federal law. Mexico has recently enacted a comprehensive new water pollution code

that, if enforced, could have significant implications for global climate change. In addition, under Minute 242 of the Mexican Water Treaty of 1944, the International Boundary and Water Commission, composed of Mexican and American representatives, has jurisdiction, at a minimum, over sewage effluent and salinity pollution affecting the Rio Grande. In 1989 it adopted water quality as its number one priority. It serves as a source of funds for resolution of these problems as they impact both nations and as a possible political forum for affected parties from both nations. All of these provisions would be under great stress as a result of global climate change and would require extensive renegotiation.

Finally, state laws, with respect to both quantity and quality for each of the three states and Mexico, will be placed directly under stress by any basic change in water supply. As discussed more fully below, the operation of this state law machinery raises very complicated legal issues that would be triggered by global climate change. For example, as water becomes a more scarce resource, the price will rise and attempts will be made to transfer the resource to higher valued uses. The transfer process is governed by extensive legal rules that will be tested. A few of the most basic issues that will arise include (1) a determination of the quantum of proof that will be placed on the buyer and seller to show that the transfer will benefit the community at large from an economic and policy standpoint and (2) the legal issues of protecting Indian and federal reserved water rights, wetlands, and the public welfare in the context of these attempted market transfers under state law.

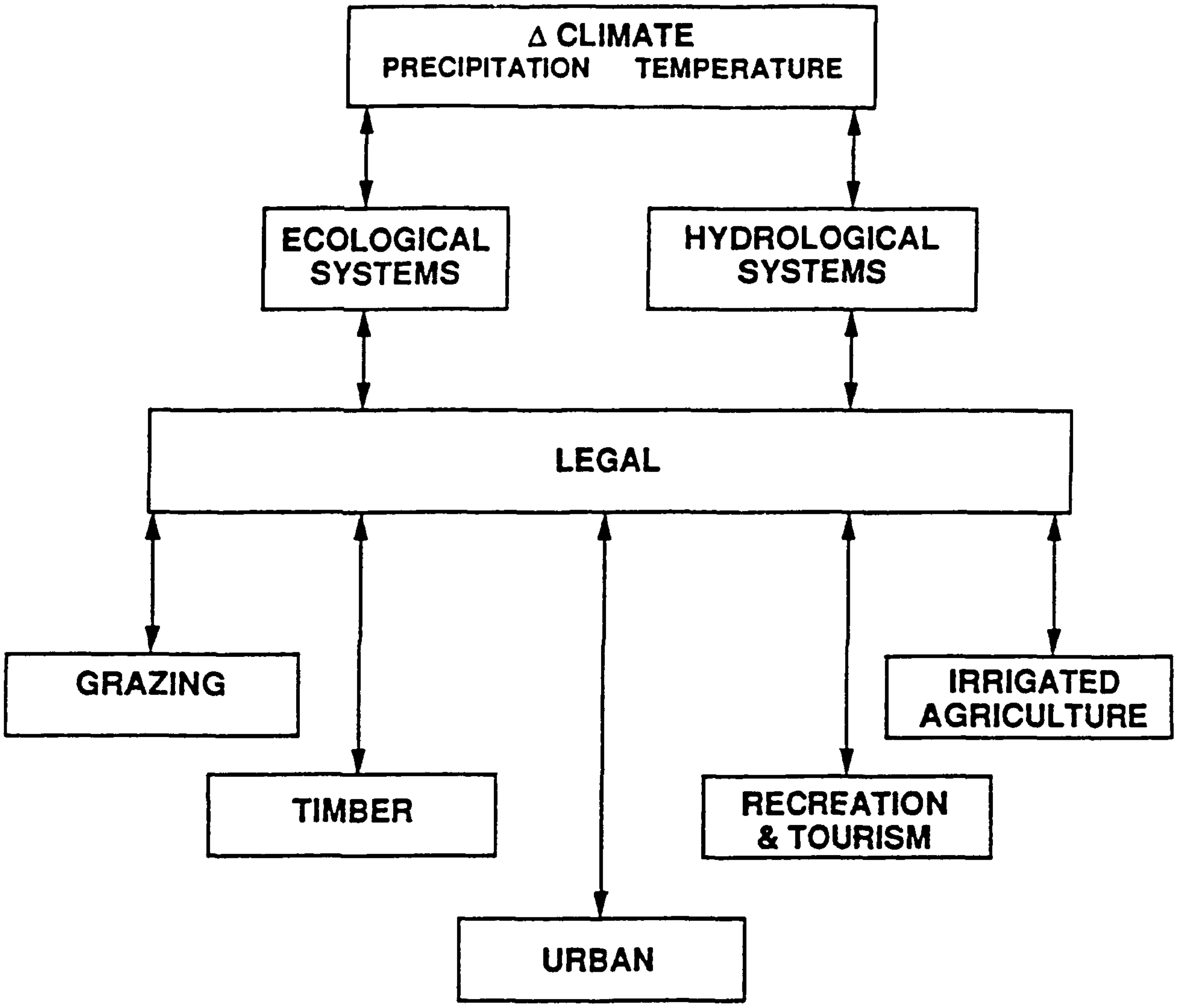
THE CASCADE OF GLOBAL CLIMATE CHANGE EFFECTS: THE IMPACTS ON AGRICULTURE

Figure 4 demonstrates the cascade of interrelated effects of changes in precipitation and temperature on ecological and hydrologic systems, the legal institutions that regulate them, and the products produced by various sectors of the economy. Tables 2 through 7 list examples of concrete impacts on these economic sectors as a result of change. Both precipitation and the temperature changes affect hydrologic systems, and these systems themselves are affected by institutional responses to climate change. For the purpose of illustration, and without suggesting agriculture impacts would be more significant than others, I will illustrate this principle using agriculture in the middle Rio Grande Valley.]

Assuming that global climate change caused an increase in temperature and a decrease in precipitation, the following interrelated impacts might occur. First, an increase in temperature would likely decrease precipitation in the winter, thus reducing the water supply available for spring runoff. If this were the case, then the quality of the water would change, because there would be less snowmelt to offset the more saline water coming in as flood flows from lower tributaries. There would also be a decrease in quality because there would be less streamflow to offset the impacts of discharges from municipalities into the stream and from storm runoff. An inevitable shift to groundwater would occur, which would add lift costs for the water. (These lift costs would raise the price of growing crops and, in turn, change the crop mix.) The value of farmland would go down because of the increased cost of farming, and the value of the groundwater rights would go up because of the reliability factor and the scarcity of surface water. The increasing demand for groundwater and the increased pumping would often hasten the rate of saline encroachment into the groundwater table due to overstressing of the aquifer.

The increased urban demand for groundwater would cause farmers to sell their water rights to urban users, which would cause a decrease in productivity of secondary industries supporting the farming industry. The decrease in farming would also cause a change in the property tax base and result in more movement to urban centers.

All of the wildlife indirectly dependent upon farming return flows would be impacted as would the wetlands. This in turn would impact the tourist industry.



Source: Proposal submitted to EPA March, 1990, "Potential Impacts of Climate Change on Rio Grande Basin," by Sandia National Laboratories, the University of New Mexico Rio Grande Basin Interdisciplinary Group.

Figure 4. **Schematic diagram of the climate impact cascade.**

Table 2

Possible Impacts on Ranching

Physical

1. Change in production of biomass
2. Change in stock levels and quality
3. Land degradation
4. Change in pests and disease
5. Change in water quantity and quality

Economic

1. Changed income from beef
2. Changed income from real estate market
3. Changed value of land and property
4. External costs of land degradation (sediments)
5. Changed consumer cost for beef
6. Changed grazing fee revenue
7. Changed secondary income (meat processing, feedlots, etc.)
8. Changed income and property tax base

Social

1. Changed assets
2. Changed standard of living
3. Health and nutrition
4. Emigration
5. Security
6. Changed social services due to declining tax base
7. Threat to culture (Native American in particular)
8. Changed employment and income stability

Source: Proposal submitted to EPA March 1990, "Potential Impacts of Climate Change on the Rio Grande Basin," by Sandia National Laboratories, University of New Mexico Rio Grande Basin Interdisciplinary Group.

Table 3

Possible Impacts on Farming

Physical

1. Change in water quantity and quality
2. Change in production of crops
3. Change in mix of crops
4. Land degradation
5. Change in flood hazard
6. Change in pests and disease

Economic

1. Changed income from crops
2. Changed income from real estate market
3. Changed value of land and property
4. External costs of land degradation (sediments)
5. Changed consumer cost for agricultural products
6. Changed secondary income (food processing, distribution, etc.)
7. Changed income and property tax base

Social

1. Changed assets
2. Changed standard of living
3. Health and nutrition
4. Emigration
5. Security
6. Changed social services due to declining tax base
7. Threat to culture (Native American in particular)
8. Changed employment and income stability

Source: Proposal submitted to EPA March 1990, "Potential Impacts of Climate Change on the Rio Grande Basin," by Sandia National Laboratories, University of New Mexico Rio Grande Basin Interdisciplinary Group.

Table 4

Possible Impacts on the Urban Unit

<u>Physical</u>

1. Changes in water quantity and quality
    a. Changes in requirements for water use
    b. Changes in water availability
        i. Salinity of return flows
        ii. Sewage discharge dilution
        iii. Quality of rainstorm runoff
    c. Effects on localized pumping

2. Changes in comfort and aesthetic factors
    a. Pollen
    b. Dust
    c. Acid precipitation
    d. Humidity
    e. Temperature
    f. Pests
    g. Weeds

3. Changes in energy use

4. Adaptive technologies in response to water and energy changes

<u>Economic</u>

1. Change in cost of water
2. Possible recycling costs
3. Change in cost of water rights
4. Change in attractiveness to water-using industries
5. Change in property value
6. Change in infrastructure

<u>Social</u>

1. Decertification and browning
2. Changes in environmental awareness
3. Attractiveness of area relative to other places
4. Changes in comfort and aesthetics
5. Possible conservation restrictions
6. Changes in demographics

Source: Proposal submitted to EPA March 1990, "Potential Impacts of Climate Change on the Rio Grande Basin," by Sandia National Laboratories, University of New Mexico Rio Grande Basin Interdisciplinary Group.

Table 5

Possible Impacts on Recreation and Tourism

Physical

1. Changes in water flow, storage, and quality
   a. Impact on water sports
   b. Changes in fish and game populations
2. Changes in snowpack and impact on snow sports
3. Changes in fire hazard
4. Changes in camping restrictions
5. Changes in air quality
6. Changes in infrastructure

Economic

1. Changes in tourism income
2. Changes in recreation costs
3. Changes in license fee revenues
4. Changes in fire-fighting costs
5. Changes in employment

Social

1. Reduced recreation opportunities
2. Lower quality of recreation experience
3. Changes in recreation mix

Source: Proposal submitted to EPA March 1990, "Potential Impacts of Climate Change on the Rio Grande Basin," by Sandia National Laboratories, University of New Mexico Rio Grande Basin Interdisciplinary Group.

Table 6

Possible Impacts on Timber

Physical

1. Change in fire hazard
2. Change in yield
3. Change in stand mix
4. Change in pests and disease
5. Change in reforestation
6. Change in water quantity and quality
7. Impact on species

Economic

1. Changes in timber assets and revenues
2. Changes in employment and income
3. Changes in wood-product costs
4. Changes in reforestation expense
5. Changes in fuel-wood prices
6. Changes in costs to meet environmental regulations

Table 7

Possible Impacts on Energy

Physical

1. Change in cooling-water availability
2. Change in process-water availability
3. Changes in heating and cooling requirements
4. Change in renewable energy use

Economic

1. Change in energy prices
2. Change in energy availability
3. Change in energy resource income
4. Change in renewable energy

Social

1. Demographic changes
2. Life-style changes
3. Job availability changes

Source: Proposal submitted to EPA March 1990, "Potential Impacts of Climate Change on the Rio Grande Basin," by Sandia National Laboratories, University of New Mexico Rio Grande Basin Interdisciplinary Group.

The rural Hispanic villages dependent on the water supply for farming would likely cease farming because the cost of drilling wells would exceed the value of farming. The Native American cultures would likewise be impacted and would seek political support in Washington to continue their irrigation with groundwater. Their interests would be pitted directly against the non-Native American agribusinesses that would be competing for tax dollars to subsidize their agricultural development. The environmental constituents would seek the remaining surface water to promote their wetlands interests, while the agricultural and urban interests would seek to use this water supply offstream for irrigation and domestic consumption.

The competition for scarce surface water resources would *inter alia* drive up the price, increase activity in the water market, promote conservation, and push a shift to groundwater. The discussion below illustrates that, unfortunately, existing legal institutions are not adequate to allow society to adapt to these changes, either as a matter of efficiency or equity.

As to increased trading in the water market, knowledge about the ownership of water rights is not adequate to accommodate a rapid increase in market activity. The water rights in the Rio Grande have not been adjudicated. While light trading does take place under current conditions, those who trade purchase only the clearly senior water rights. There are thousands of acre-feet water in use that are unclear as to ownership. The title to these rights could be vested in the irrigation or conservancy districts, the United States under reclamation law, or the Indian tribes under the federal reserved water rights doctrine. There is no quick way to solve this problem. Adjudication suits can take up to 25 years or more.

Assuming *arguendo*, that one clarified the ownership interests, the criteria applied by the state when allowing transfers, including the nature of the interests that can be considered when rights are sold from one use to another, are not clear. This lack of legal clarity would cause extensive hearings and lead to great legal expense as environmentalists and native populations clash with urban and agricultural interests in the water rights transfer process.

The Rio Grande Compact was a compromise hammered out between states based on fixed assumptions as to water supply. It was, of course, anticipated that flow would vary somewhat from year to year. Texas receives a greater proportionate share in high-flow years and New Mexico in low-flow years. If the flow were dramatically reduced, Texas and southern Rio Grande New Mexico farmers could barely stand the catastrophic impact of water scarcity. Texas farmers would likely go to court to seek to invalidate the compact. New Mexico might in turn seek similar relief against its upstream neighbor, Colorado. The argument would be that a compact is like a contract between states. To be valid at its inception, it must be based on true information. If the commodity that was the subject of the contract is inadequately defined, then the contract is void for a lack of a meeting of the minds as to what was bargained for. They would argue that global climate change has altered the bargain and voided the contract. Relief in the courts or in Congress would not come quickly. The compact contains no clear reallocation mechanism in the event of significant scarcity and is not adequate to address a global climate change circumstance.

Federal and state agencies would need to reevaluate all of their policies relating to stream discharges, since all permits would be allowing a disproportionately large amount of pollutants due to decreased streamflow. The number of species on the Endangered Species list would rise up dramatically since surface-water habitat would have been reduced. Well locations monitoring of drawdown effects would have to be increased extensively, since groundwater pumping would be showing a dramatic increase. Wetlands protection under the Clean Water Act would have to be increased, since the quantity of surface water for wetlands would be decreased. As currently written, neither the Clean Water Act nor the Safe Drinking Water Act is flexible enough to adjust to the stress of global climate change. The bureaucratic time lag for National Pollutant Discharge Elimination System (NPDES) permits and Section 404 clearance of wetlands is already long. Those seeking relief under the acts would likely run into bureaucratic paralysis.

Finally, the Mexican Water Treaty of 1906, which requires delivery of 60,000 acre-feet from the Rio Grande to Mexico at Fort Quitman, Texas, would be the subject of renegotiation. Given the porous nature of the riverbed, delivery in extremely water-short years would be extremely wasteful. A logical substitute would be groundwater. However, since there is no treaty between the two countries regulating groundwater pumping at the border, no mechanism exists for making this change. The likely result would be that the surface-water issues and under-deliveries would find themselves *sub silentio* on the table during discussions of trade and immigration. These are not the appropriate forums for natural resources issues; but by default, they might wind up there.

CONCLUSIONS

The above discussion illustrates that legal institutions are not currently adequate to address the impacts of global climate change on irrigated agriculture. The state laws, federal laws, interstate compacts, and international treaties are also inadequate to meet the challenges relating to grazing, timber, recreation, and urban uses. Global climate change would cause a cascade of events to be dealt with by politicians, lawyers, and judges. At this point, they would reach gridlock because all of these laws as written are based on one fundamental assumption--the globe and its climate do not change. Wise administrators and decision-makers would act now to correct these inadequacies if they believe that climate change may become a reality.

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THE IMPLICATIONS OF CLIMATE CHANGE FOR WATER RESOURCES IN THE COLORADO RIVER BASIN

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ABSTRACT

Changes in regional temperature and precipitation expected to occur as a result of the accumulation of greenhouse gases may have significant impacts on water resources. In this study, we used both conceptual hydrologic model and a reservoir-simulation model to study the sensitivity of surface runoff and water supply in the Colorado River to these changes. Increases in temperature of 4°C caused mean annual runoff to decrease by 9 to 21 percent. Increases or decreases in annual precipitation of 10 to 20 percent resulted in corresponding changes in mean annual runoff of approximately 10 to 20 percent. Persistent changes of 5 to 20 percent in natural streamflow had significant effects on water storage, consumptive use, hydroelectricity generation, and salinity throughout the basin. Over a 78-year period, changes in reservoir storage and electricity production ranged from an average annual decrease of roughly 60 percent under the -20 percent scenario to an increase of 40 percent under the +20 percent scenario, indicating that both of these variables are very sensitive to changes in natural flow. Lesser, but significant, changes in consumptive use and salinity also occurred. Overall, we find that water supply in the Colorado River basin is very sensitive to the magnitude of changes contemplated here. These results suggest that past assumptions about water management and policy will face increasing challenges as we try to balance many more competing demands amidst additional climate uncertainty.

INTRODUCTION

The Colorado River is one of the most important river systems in the United States. Although not a large river, even in comparison to other rivers in the United States, the Colorado flows through some of the most arid regions of the country and is the primary source of water for an area with extensive agriculture, large cities, and a diverse ecosystem. The Colorado River basin covers approximately 243,000 square miles, parts of seven states, and reaches into Mexico. Annual flow of the Colorado River at Lee Ferry has ranged from 5.6 million acre-feet (maf) to 24.0 maf since regular streamflow recording was initiated in the early part of this century. (One acre-foot is equivalent to 1,233 cubic meters. A flow of one cubic meter per second (cms) is equal to 70.02 acre-feet per day.) Over the same period, mean annual runoff has been about 15.1 maf. However, tree-ring analyses dating back to 1512 have suggested that the long-term mean may be closer to 13.5 maf (Stockton and Jacoby, 1976).

Existing global models suggest that climate changes will have dramatic impacts on water resources. Water availability, quality, and demand will be affected by higher temperatures, new precipitation patterns, rising sea level, and changes in storm frequency and intensity (IPCC, 1990). These changes will be important to the Colorado River basin because of their effect on water supply and water management--issues that are already contested in the region. Moreover, potential climate impacts will have significant ramifications for decisions about water allocations and water rights that are likely to be made in the coming decade.

To date, few studies have attempted to model the impacts of climate change on regional water supply systems. This reflects both the lack of suitable models and the paucity of regional information on climate-induced changes in runoff. Two exceptions are the studies of the State Water Project in California and the Tennessee Valley Authority, both done as part of the EPA study of climate impacts (U.S. EPA, 1989). In these studies, a limited number of GCM scenarios were analyzed using large-scale water supply models. In both cases, water supply systems were found to be quite sensitive to GCM-derived scenarios of climate change. In this study, a regional hydrologic model was used to assess the effects of changes in temperature and precipitation on runoff. Subsequently, a reservoir-simulation model was used to assess the effect of changes in runoff on future water supply (see Figure 1).

The regional hydrologic model used in this study was a conceptual model, developed and operated by the National Weather Service River Forecasting System (NWSRFS) in Salt Lake City, Utah (Burnash et al., 1974; Anderson, 1973). This model has advantages and limitations, described in detail in Nash and Gleick (1991), but its success as a forecasting tool indicates that the model has the capability to simulate the effects of changes in temperature and precipitation, particularly for moderate changes in these climate variables (Nemec and Schaake, 1982). The NWSRFS models the upper Colorado River basin as a series of approximately 50 small sub-basins that are linked together. In addition, an aggregated model has been developed that divides the entire upper Colorado river basin into two elevation zones and uses a limited number of meteorological stations to predict inflow into Lake Powell. In addition to the two-elevation model, we selected three sub-basins that were known to make a substantial contribution to basin flow: the White River at Meeker, the East River at Almont, and the Animas River at Durango (see Figure 2).

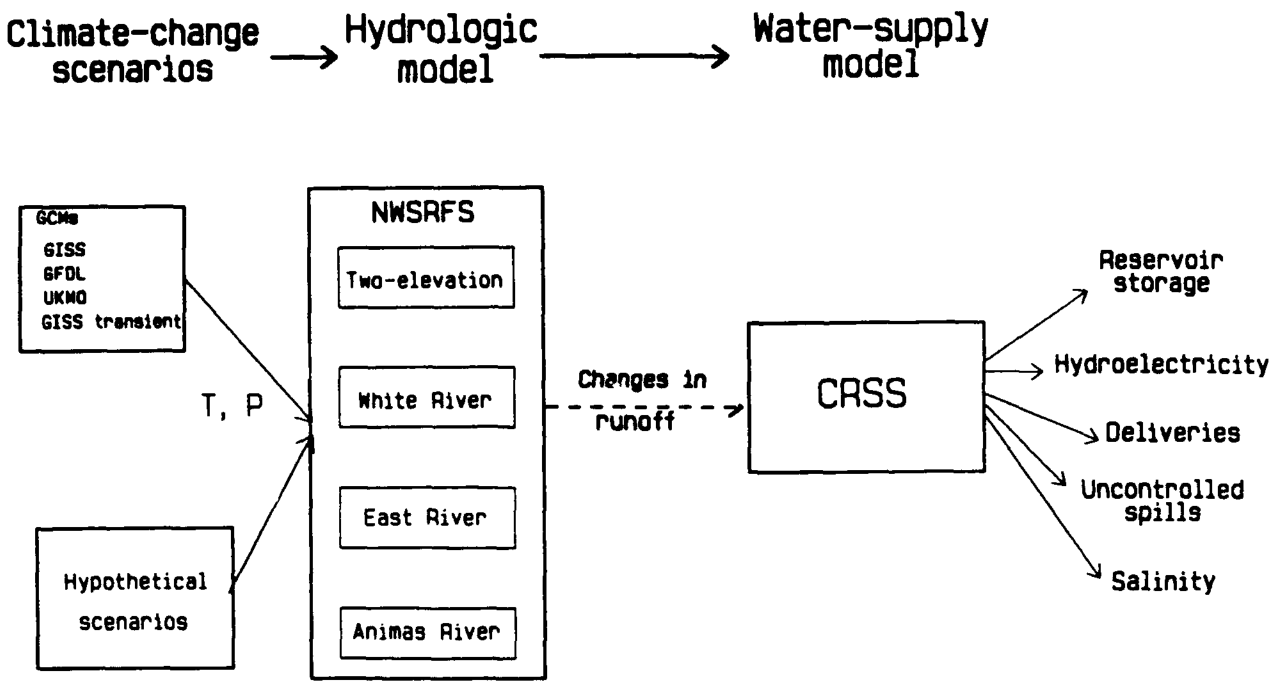
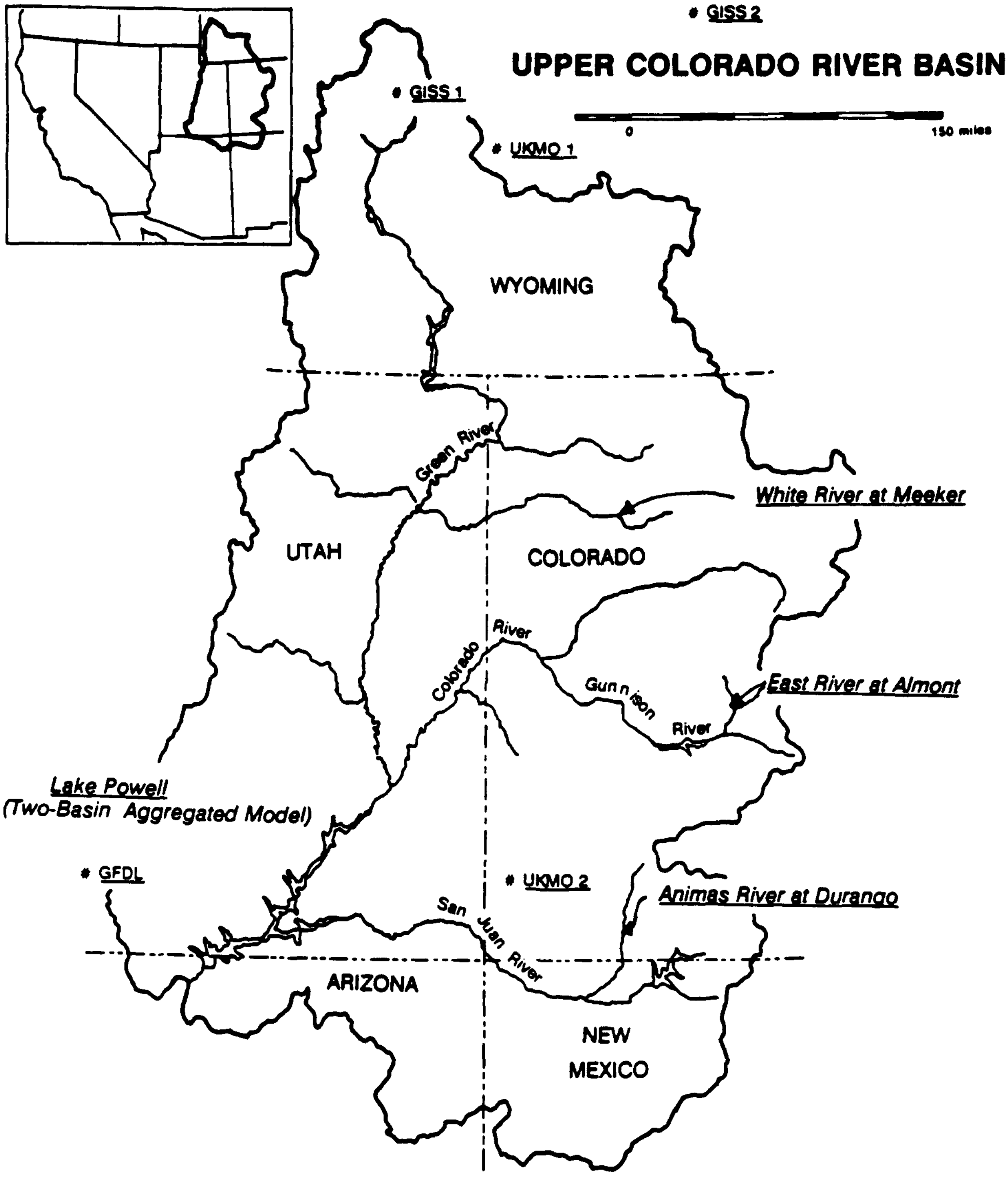


Figure 1. **Schematic illustrating the concept of the study and the relationship among various models. Potential changes in temperature and precipitation were derived from GCMs and hypothetical scenarios; these changes were then applied to four regional hydrologic models, which are all part of the larger NWSRFS model. Finally, scenarios of change in runoff were derived from the NWSRFS model results and applied to the CRSS model in order to generate potential changes in water supply variables.**



(redrawn from Upper Colorado Region Comprehensive Framework Study, Main Report, June 1971)

Figure 2. **Map of the upper Colorado River basin, showing the location of the hydrologic sub-basins that were modeled as well as the location of relevant GCM grid points.**

To assess the potential impacts of climate change on runoff in the Colorado River basin, scenarios of changes in temperature and precipitation were used as inputs into the NWSRFS model. For this study we relied on purely hypothetical scenarios as well as scenarios derived from the outputs of general circulation models (GCMs). The hypothetical scenarios studied include temperature increases of 2°C and 4°C combined with precipitation changes of ±10 and ±20 percent. The GCM scenarios used in this study include temperature increases that range from 4°C to 7°C combined with precipitation changes that range from zero to +30 percent (see Table 1). These scenarios were applied to the model's baseline data, which consist of six-hourly data for the years 1949 through 1983, inclusive.

Using the results of the NWSRFS model, we chose a range of plausible runoff scenarios with which to assess the sensitivity of the basin to changes in water supply. The impact of changes in runoff on water deliveries, hydropower production, reservoir levels, and several other variables was studied with the Bureau of Reclamation's Colorado River Simulation System (CRSS). The CRSS is a reservoir-simulation model that tracks streamflow and water supply throughout the Colorado River basin and is documented in U.S. DOI (1987).

The CRSS uses historical streamflow data (a 78-year record, extending from 1906 to 1983) to analyze possible future conditions. The input to the model is "natural" streamflow--defined as historical flow data adjusted to remove the effects of human development--at 29 gauging stations throughout the basin. The output from the model is actual streamflow, reservoir levels, hydropower production, reservoir spills, salinity, and water deliveries. River operations in the model are determined by a variety of reservoir operating criteria that are designed to reflect the legal and administrative requirements that govern water supply in the basin. The series of compacts, treaties, laws, court decisions, and regulations that establish the priorities among the Colorado River's multiple users is known collectively as the "law of the river." These requirements are summarized in detail in Hundley (1975) and Getches (1991). The law of the river, in turn, dictates certain reservoir operating criteria. The principal operating

Table 1.

Changes in Temperature and Precipitation in the Colorado River Basin Predicted by General Circulation Models (GCMs) [1]

	Δ Temperature (°C)	Δ Precipitation (%)
GISS 1	+4.8	+20
GISS 2	+4.9	+10
GFDL	+4.7	0
UKMO 1	+6.8	+30
UKMO 2	+6.9	+10

Note: [1] All GCM scenarios are derived from equilibrium runs, in which greenhouse gas concentrations at roughly twice current levels. For comparison and discussion of the different GCMs, see IPCC (1990).

parameter in the model is an objective minimum release of 8.23 maf/year from Lake Powell. In addition, the model incorporates the storage and flood control requirements and implements the Bureau of Reclamation's shortage and surplus strategies. The primary operating constraints that affect operation of the model are documented in the Department of Interior publication, *Updating the Hoover Dam Documents* (U.S. DOI, 1980) and are also described in U.S. DOI (1987). The CRSS does *not* model water rights priorities or the potential for compact calls (that is, the potential for the lower basin to require the upper basin to curtail usage in order to meet the requirements of the Colorado River Compact). Instead, shortages are passed to downstream users.

For the purposes of this study, operating procedures (for example, rule curves or target storages) were held constant and the natural flow data base was uniformly altered by ±5, ±10, and ±20 percent. The magnitude of these changes corresponds roughly to the results generated by the NWSRFS model, which suggested that changes in runoff in the higher elevations of the upper basin were likely to range from -30 to +10 percent (discussed below). Although it is likely that operational parameters would be adjusted over time to increase the system's efficiency with respect to changed hydrologic conditions, such changes would be implemented slowly and only after a general acknowledgment of changed conditions. At this point, it is difficult to estimate to what extent changes in operations might mitigate the impacts of changes in flow; this is an area for further research.

Our results summarize a model run of 78 years in which natural flows were altered by the specified percentage at all 29 input stations. Reservoir evaporation rates were unchanged, even though they would be expected to increase significantly under conditions of higher temperature. The demand data used in these runs were the Bureau of Reclamation's projections for the year 2040 and were held constant for the period analyzed (see Table 2). For the model runs presented in this paper, the total amount of reservoir storage at the beginning of the run was approximately 36.5 maf, or about 60 percent of the system's total storage capacity.

Table 2.

Scheduled Demands (taf) Used by the Bureau of Reclamation in the CRSS Model [1]

Year	Upper Basin	Lower Basin			Mexico	Total
		MWD	CAP	Other [2]		
1990	3,916	518	1,515	5,772	1,515	13,236
2000	4,490	497	1,488	5,911	1,515	13,901
2010	4,801	497	1,464	5,935	1,515	14,212
2020	4,973	497	1,464	5,960	1,515	14,409
2040	5,245	497	1,464	5,992	1,515	14,716

Notes: [1] Although trended demands are given here for the years 1990 to 2040, demands were held constant at 2040 levels in the model runs analyzed.

[2] Lower Basin demands other than those of MWD and CAP.

RESULTS

Hydrologic (NWSRFS) Model

Large changes in the magnitude of annual flow in the Colorado River basin may result from plausible climate changes. A 2°C rise in temperature corresponds to a decrease in runoff of 4 percent on the White River, 9 percent on the East River, and 7 percent on the Animas River. For the two-elevation model, a temperature increase of 2°C could reduce runoff by 12 percent, excluding the effect of higher temperatures on reservoir

evaporation. An increase of 4°C decreases runoff by between 9 and 21 percent. Increases and decreases in precipitation of 10 and 20 percent led to equivalent changes (10 to 20 percent) in runoff. All relationships between runoff and precipitation are nearly linear for the range of scenarios studied (see Figure 3), with the exception of the T+4°C scenarios on the East River. In the latter case, runoff increases more slowly than precipitation. Overall, runoff in the White River is slightly less affected by temperature increases than are the Animas and East rivers, while runoff is considerably more sensitive to temperature in the two-elevation model.

For the Animas and East rivers, all GCM scenarios led to decreases in runoff, ranging from -8 to -20 percent, which reflects the dominant effect of increased evaporation. For the White River, two out of the four GCM scenarios showed increases in runoff (of 10 to 12 percent), while the other two scenarios resulted in decreases in runoff (of -8 to -10 percent). For the two-elevation model, three of the four GCM scenarios resulted in decreases in mean annual runoff ranging from -14 to -24 percent. The fourth scenario resulted in an increase of less than 1 percent.

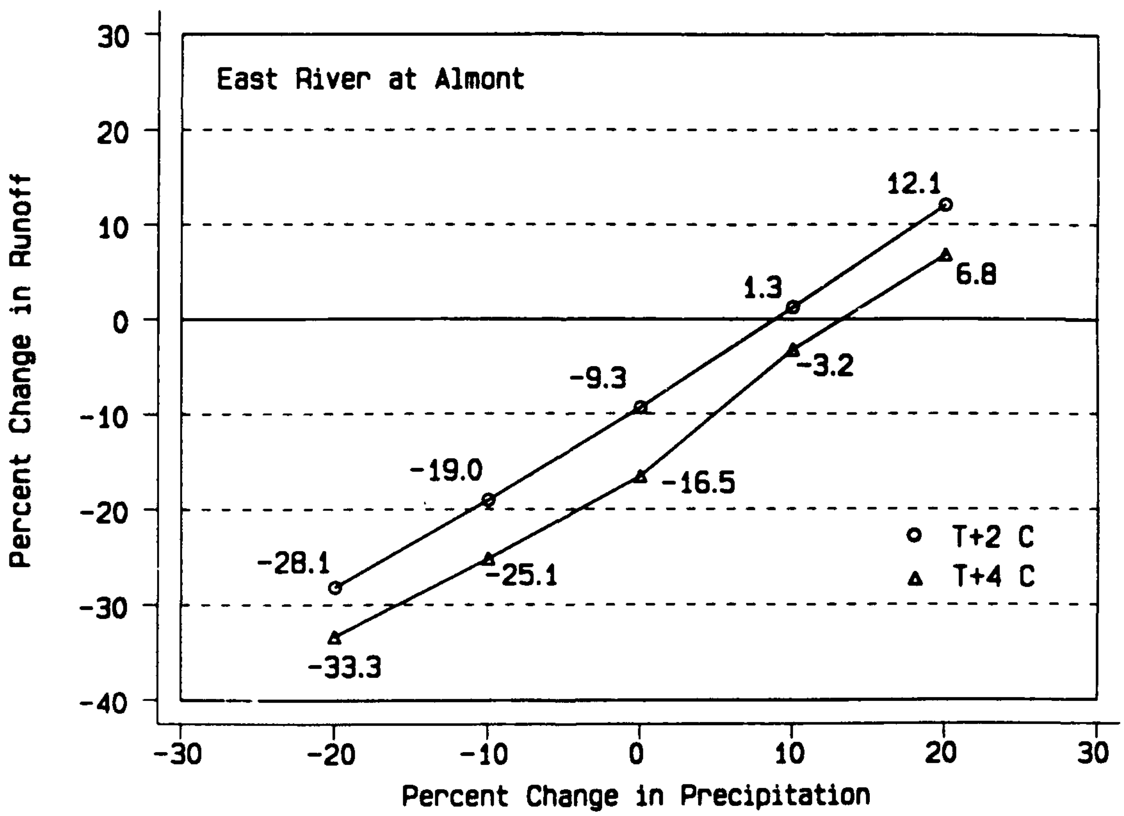


Figure 3. **Impact of changes in temperature and precipitation on mean annual runoff for the East River model. The relationship between changes in precipitation and changes in runoff is nearly linear for the range of hypothetical scenarios analyzed.**

Temperature increases cause peak runoff to occur earlier in the year. A temperature increase of 2°C shifts peak runoff from June to May for the White and Animas rivers and for the two-elevation model. For the East River, peak runoff still occurs in June, although it is not nearly so exaggerated. For all three basins, the 2°C rise creates a double peak, with runoff in May and June being nearly equal. When temperature is increased by 4°C, the East River also undergoes a distinct shift in the timing of peak runoff, from June to May. The United Kingdom Meteorological Office (UKMO) scenario for the Animas and White rivers shifts peak runoff from June to April, which reflects the larger 6.8°C temperature rise for this GCM.

Reservoir-Simulation (CRSS) Model Results

Results from the CRSS model are summarized in Table 3. A 20 percent decrease in natural flow causes an 11 to 31 percent decrease in modeled flow at the five points analyzed (Green River at Green River, Wyoming; Colorado River at Cisco; San Juan River at Bluff; Colorado River at Lee Ferry; and Colorado River at Imperial Dam). A 20 percent increase in natural flow causes a 31 percent increase in modeled flow at each of the five points analyzed. For the upper basin points, a 5 percent change in natural flow causes a 7 to 8 percent change in actual flow, and the effect of changes in natural flow is essentially linear over the range of scenarios examined. This is not true in the lower basin where storage has a greater impact on flow.

Much of the difference in flow generated by the climate-change scenarios, rather than being passed through the system, is being cushioned through increased water storage or increased releases. While the natural flow data that are input into the model refer to a condition in which no storage exists, actual storage throughout the entire Colorado River system is about 60 maf, or approximately four times the average annual flow of the river at Lee Ferry. It is this storage capacity that is cushioning annual changes in streamflow, particularly in the lower basin.

Table 3.

Sensitivity of Water-Supply Variables to Changes in Natural Runoff in the Colorado River Basin [1]

Change in Natural Runoff (%)	Change in Actual Runoff (%)	Change in Storage (%)	Change in Power Generation (%)	Change in Depletions (%)	Change in Salinity (%)
-20	(10-30)	(61)	(57)	(11)	15-20
-10	(7-15)	(30)	(31)	(6)	6-7
-5	(4-7)	(14)	(15)	(3)	3
5	5-7	14	11	3	(3)
10	11-16	28	21	5	(6-7)
20	30	38	39	8	(13-15)

Note: [1] Numbers in parentheses represent DECREASES.

Reservoir storage is reported as storage on August 1, which corresponds to the end of the spring runoff season and is roughly when peak storage occurs in the Colorado system. In the upper basin reservoirs, increases in flow of 5, 10, and 20 percent generate respective increases in storage of approximately 18, 25, and 30 percent. Decreases in flow of 5, 10, and 20 percent generate respective decreases in storage of 16, 30, and 65 percent. For Lake Mead, the major lower basin reservoir, these figures are comparable. For both the upper and lower basins, a 20 percent increase in natural flow generates completely full reservoirs. Decreases in natural flow of 20 percent reduce mean storage on August 1 in Lakes Powell and Mead to less than 25 and 15 percent of their respective capacities.

More interesting than average changes in storage is how frequently critical storage levels are reached under various scenarios (see Figures 4 and 5). For instance, in the base case, Lake Powell never falls below minimum power pool. The -5 percent scenario causes Lake Powell to fall below its minimum power pool (4 maf) roughly 20 percent of the time; this frequency increases to nearly 60 percent under the -20 percent scenario. Similarly, in the base case, the frequency with which Lake Powell contains 2 or more years of storage (roughly 16.5 maf) is just under 50 percent. This frequency rises to 70 percent under the +5 percent scenario, and to 90 percent under the +20 percent scenario. The -5 percent scenario takes storage in Lake Mead to new low levels, although the reservoir recovers to base-case levels within about 10 years. The -10 percent scenario causes extended periods of very low storage, and recovery takes 15 to 20 years. In the -20 percent scenario, reservoirs are unable to recover to average levels over the modeled period. The -20 percent scenario causes Lake Mead to go dry roughly 25 percent of the time.

Consumptive water use in the basin is reported in terms of depletions and deliveries to major users. Scheduled depletions are those shown in Table 2. In addition, for some users, deliveries are constrained so that they never fall below a minimum level. In this study, the minimum deliveries for Central Arizona Project (CAP) and Metropolitan Water District (MWD) were 451 thousand acre-feet (taf) and 500 taf, respectively. As mentioned above, the CRSS has no provisions for allocating shortages in the upper basin. Thus, when shortages occur and storage is exhausted, most shortages are imposed on lower basin users, even though this may result in violations of the Colorado River Compact during the simulation run. The method by which the model allocates shortages among lower basin users is described in U.S. DOI (1987).

Average annual depletions for the upper and lower basins and Mexico, across all scenarios, are summarized in Table 4 for all model runs. Much less variation occurs among scenarios in the upper basin, where the -20 percent scenario causes only a 5 percent decrease in depletions and the +20 percent scenario causes a 2 percent increase in depletions. In the lower basin, the -20 and +20 percent scenarios result in a respective 15 percent decrease and a 12 percent increase in depletions. In the base case, deliveries to Mexico average 1,918 taf/year and never fall below the 1,500 taf level specified by the treaty requirements. Similarly, on an average basis, the lower basin receives 7,817 taf/year, which exceeds entitlements by 300 taf. However, in 32 percent of the years, consumption in the lower basin is reduced below 7,500 taf. This rises to 58 percent in the -5 percent scenario, 69 percent in the -10 percent scenario, and 100 percent in the -20 percent scenario. Mexico receives its full commitment in the base case and in the -5 percent scenario. It suffers shortfalls in 6 percent of the years in the -10 percent scenario, and in 36 percent of the years under the -20 percent scenario.

Hydroelectricity production, like reservoir storage, is extremely sensitive to changes in runoff. The -10 percent scenario causes average annual storage to decrease by 30 percent while power production decreases by only 31 percent. In the -20 percent scenario, power production drops by 57 percent compared to a decline in storage of 61 percent. Storage increases, however, tend to exceed power increases on a percentage basis. In the +5 percent scenario, overall power generation jumps by 1 million gigawatt-hours (GWh) per year, or 11 percent, while storage increases by 14 percent. In the +10 percent scenario, power generation increases by 21 percent, compared to an increase in storage of 28 percent.

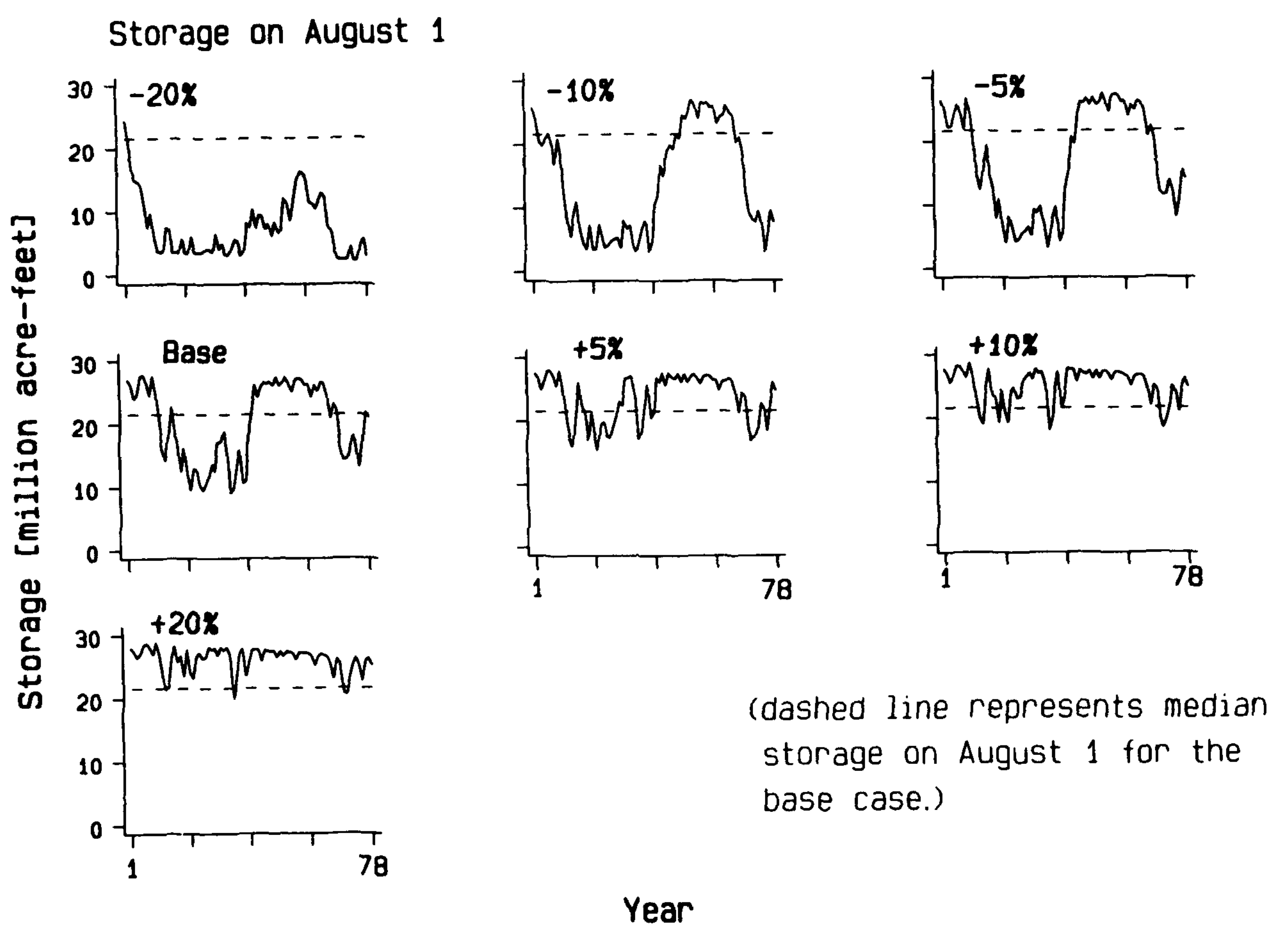


Figure 4. **Impact of changes in runoff on reservoir storage in the upper Colorado River basin. Storage is reported as of August 1, which represents the end of the spring runoff season and is roughly the date of maximum storage in the Colorado system. Reservoirs were at roughly 60 percent of capacity at the beginning of the simulation period.**

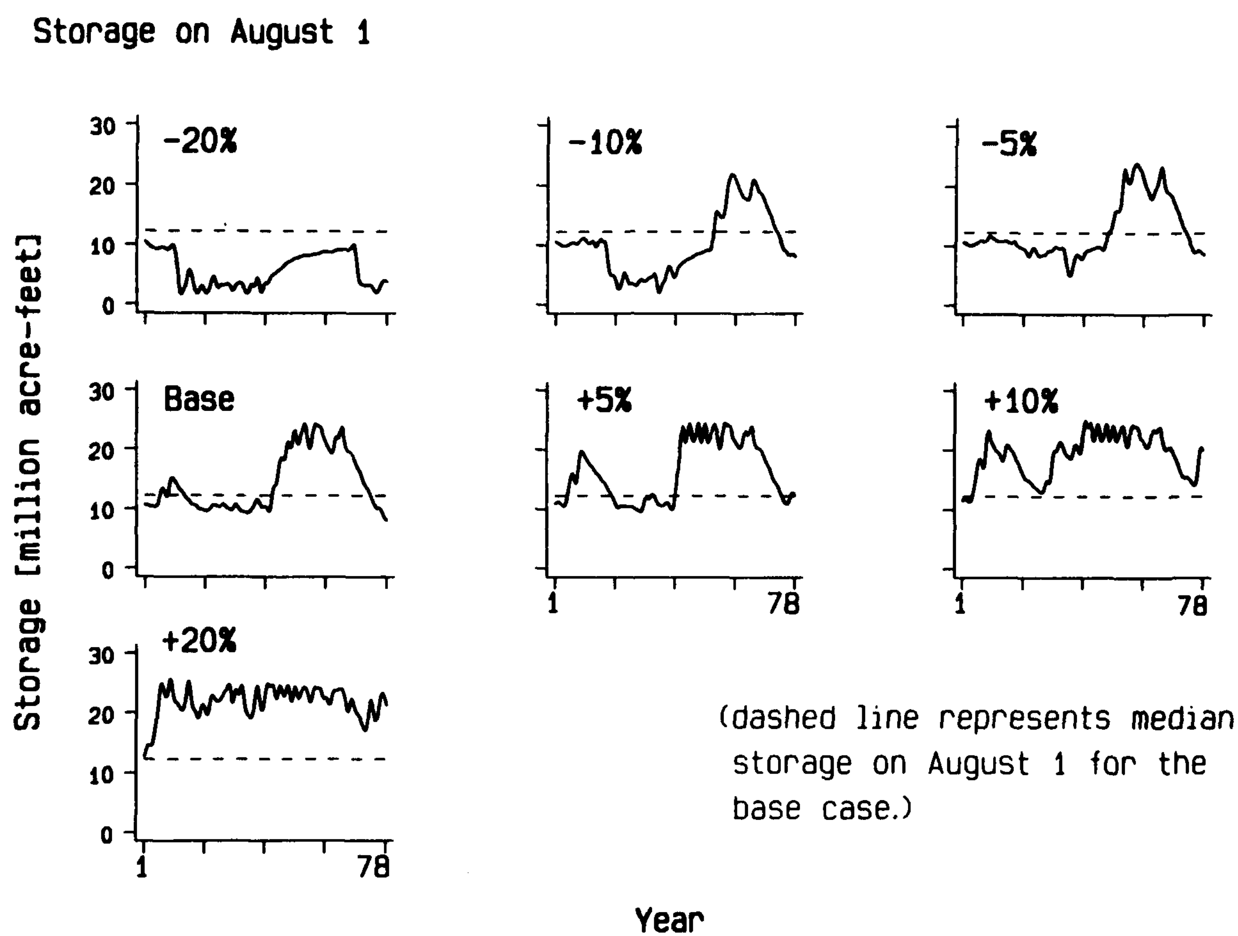


Figure 5. **Impact of changes in runoff on reservoir storage in the lower Coloardo River basin. Storage is reported as of August 1, which represents the end of the spring runoff season and is roughly the date of maximum storage in the Colorado system. Reservoirs were at roughly 60 percent of capacity at the beginning of the simulation period.**

Table 4.

Average Annual Consumptive Use (taf) in the Upper and Lower Basins and Mexico

Scenario	Upper Basin [1]		Lower Basin		Mexico		Total	
-20 %	4,822	(-5.1 %)	6,611	(-15.4 %)	1,366	(-28.8 %)	12,799	(-13.6 %)
-10 %	4,964	(-2.3 %)	7,132	(-8.8 %)	1,500	(-21.8 %)	13,595	(-8.2 %)
-5 %	5,016	(-1.3 %)	7,443	(-4.8 %)	1,684	(-12.2 %)	14,143	(-4.5 %)
Base	5,080		7,818		1,919		14,816	
+5 %	5,115	(0.7 %)	8,121	(3.9 %)	2,232	(16.3 %)	15,468	(4.2 %)
+10 %	5,137	(1.1 %)	8,363	(7.0 %)	2,607	(35.9 %)	16,108	(8.7 %)
+20 %	5,169	(1.8 %)	8,750	(11.9 %)	3,820	(99.1 %)	17,739	(19.7 %)

Notes: [1] Numbers in parentheses represent percent change compared to the base case.

In this study, no uncontrolled spills occurred in the lower basin except in the +20 percent scenario, in which spills occur in 2 out of 78 years. The total volume of spills for these years is 1.5 maf and 8.0 maf. For the upper basin, the base-case scenario generates uncontrolled spills in 4 years out of a total of 78 (5 percent), with the maximum volume of spills in any 1 year equal to 1.5 maf (see Figure 6). When natural flow is increased by 5 percent, uncontrolled spills occur in 6 years, with a maximum annual volume of 1.7 maf. A 10 percent increase in natural flow results in 14 years that experience uncontrolled spills, with a maximum annual volume of 3 maf. In the +20 percent scenario, uncontrolled spills are occurring in approximately one-third of the years. The maximum annual volume of spills in this scenario is 4.5 maf. Even though spills occur under scenarios of increased flow, the existing flood control criteria for the reservoirs, which require that 5.35 maf of storage space be available in Lake Mead or upper basin reservoirs on January 1, are never violated.

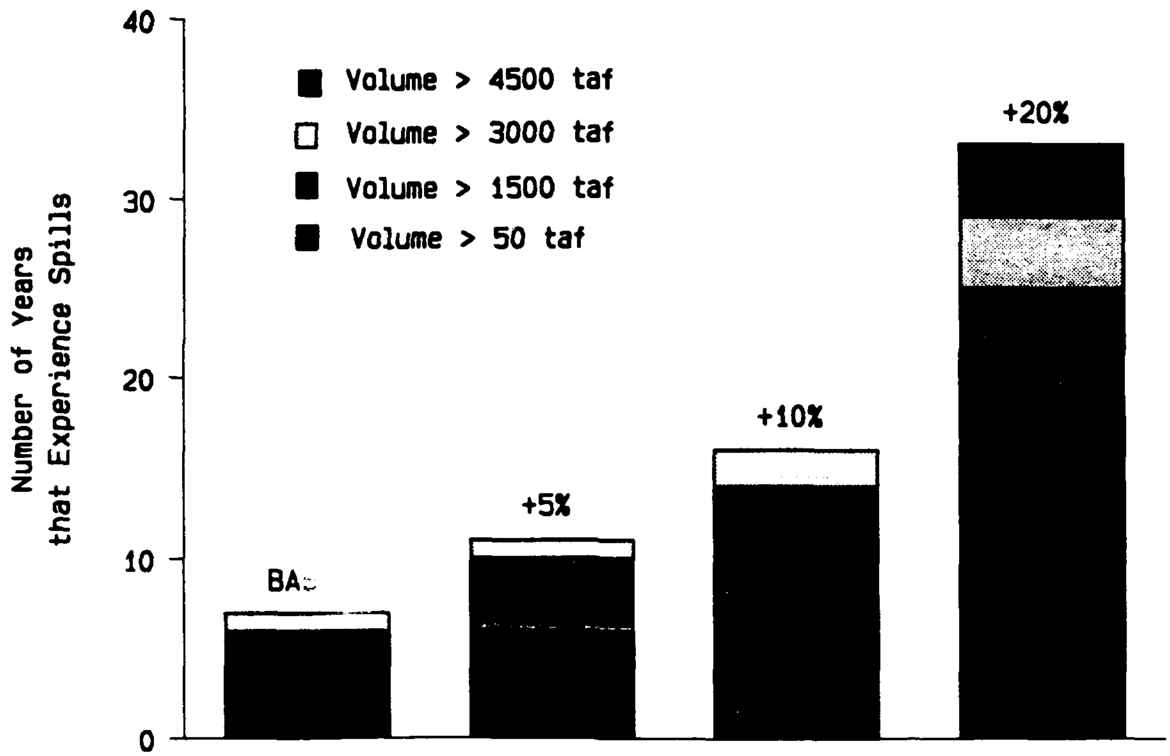


Figure 6. **Frequency and approximate annual volume of uncontrolled spills that occur in the upper Colorado River basin during a simulation period of 78 years. The number of years in which spills exceed a total of 50 taf ranges from 7 (9 percent) in the base case to 33 (42 percent) in the +20 percent runoff scenario.**

Not surprisingly, the most critical concern in the basin is water quality and salinity. Under almost no circumstances can existing water quality criteria be met given projected demands, operating constraints, and existing salinity control projects. Our results suggest that *at least* a 20 percent increase in natural runoff would be necessary to bring the salinity levels in the lower basin into compliance with existing numeric criteria. Although the scenarios considered here result in only moderate changes in salinity, the problem is already so severe in the base case that even moderate declines in water quality are of particular concern.

CONCLUSIONS

In the first study to analyze the impacts of climate change on the Colorado River, Stockton and Boggess (1979) used Langbein's relationships (Langbein et al., 1949) to estimate the effects of a 2°C temperature rise and a 10 percent decrease in precipitation. They found that streamflow in the upper basin would decline by about 44 percent. Following up on that work, Revelle and Waggoner (1983) developed a linear regression model of runoff using precipitation and temperature as independent variables. Their model predicted that a 2°C temperature increase would decrease mean annual flow by 29 percent, while a 10 percent decrease in precipitation would decrease runoff by about 11 percent. In combination, these changes would result in a 40 percent decrease in runoff, in close agreement with Stockton and Boggess' earlier result.

In contrast, our studies with the NWSRFS model suggest less severe impacts on runoff and a greater sensitivity of annual runoff to precipitation rather than temperature changes. A 2°C temperature rise combined with a decrease in precipitation of 10 percent would decrease runoff by 14 to 23 percent. While these results are lower than the earlier, statistical studies, they still indicate potentially dramatic decreases in water availability in the Colorado basin. These results are comparable to similar studies of arid/semi-arid basins that used conceptual hydrologic models (Table 5), supporting Karl and Riebsame's (1989) conclusion that the Langbein relationships overstate the role of evaporation. For the range of scenarios presented here, mean annual runoff changes nearly linearly with precipitation, although this relationship begins to break down as precipitation increases by 20 percent, at which point runoff begins to increase relatively faster.

Our analysis suggests that variations in mean annual runoff of 30 percent are possible as a result of climate change, with even greater changes likely in the most arid sub-basins, but that precipitation changes of more than 10 percent would be necessary before changes in annual runoff would be significantly different from the historical flow series (Nash and Gleick, 1991). This does not imply that the impacts of climate change are insignificant but does suggest the difficulty inherent in detecting the effects of climate change given a relatively short and variable streamflow record. The results also suggest that increases in precipitation would be needed to balance the effect that higher temperature will have on runoff. If precipitation stays the same or decreases, substantial decreases in water availability may result.

An increase in temperature shifts the seasonality of runoff as well, with peak runoff occurring earlier in the spring. This change reflects the fact that under higher temperatures more precipitation falls as rain rather than snow, and snowmelt runoff occurs earlier in the year. Because this seasonal result is induced by changes in temperature, rather than less-certain changes in precipitation, we believe it is fairly robust. Our results from the CRSS model suggest that the water supply system of the Colorado River basin is sensitive to changes in runoff that might be plausibly associated with climate change, and that some tradeoffs will be necessary to balance multiple purposes. Looking back at the hydrologic modeling discussed above, we can relate climate scenarios to the changes in the water supply variables given in Table 3. A temperature increase of 2°C and a decrease in precipitation of 10 to 20 percent corresponds, more or less, to a decrease in runoff of -20 percent. This, in turn, would cause reductions in storage of 60 to 70 percent, reductions in power generation of 60 percent, and an increase in salinity of 15 to 20 percent. A temperature increase of 2°C accompanied by an increase in precipitation of 20 percent corresponds roughly to a 20 percent increase in runoff, a 30 to 60 percent increase in storage, a 40 percent increase

Table 5.

Impacts of Climatic Changes on Runoff in Semi-Arid River Basins [1]

Change in Precipitation	Change in Temperature: T+1°C		T+2°C		T+3°C		T+4°C	
-10%	Pease River [2]	-50%	Great Basin Rivers [3]	-17 to -28%	Pease River	-50%		
			Sacramento River [4]	-18%			Sacramento River	-21%
			Inflow to Lake Powell [5]	-24%			Inflow to Lake Powell	-32%
			White River	-13%			White River	-17%
			East River	-19%			East River	-25%
			Animas River	-17%				
0			Sacramento River	-3%			Sacramento River	-7%
			Inflow to Lake Powell	-12%			Inflow to Lake Powell	-21%
			White River	-4%			White River	-8%
			East River	-9%			East River	-16%
			Animas River	-7%			Animas River	-14%
+10%	Pease River	+50%	Sacramento River	+12%	Pease River	+35%	Sacramento River	+7%
			Inflow to Lake Powell	+1%			Inflow to Lake Powell	-10%
			White River	+7%			White River	+1%
			East River	+1%			East River	-3%
			Animas River	+3%			Animas River	-5%

Notes:
[1] Each study uses different assumptions; refer to references for details.
[2] All Pease River results from Nemec and Schaake, 1982.
[3] All Great Basin Rivers results from Flaschka, et al., 1987.
[4] All Sacramento River results from Gleick, 1987
[5] All Lake Powell, White, East, and Animas River results from this study.

in power production, and a 13 to 15 percent decrease in salinity. A temperature increase of 4°C coupled with a precipitation decrease of 20 percent would result in approximately a 30 percent decrease in runoff, which is more extreme than any of the scenarios modeled with the CRSS.

It should be borne in mind, however, that these results reflect flow changes of 5 to 20 percent imposed on the hydrology of the last 80 years. The results would be different if a different hydrologic record had been used. For instance, the hydrology of the last 400 years suggests that much more severe and sustained droughts have occurred in the past (Stockton et al., 1991). If this hydrology were used as a basis for a similar study, decreases in flow would have still greater impacts on the basin.

Although we were not able to assess the impact of changes in operations as part of this study, our results suggest that the system would almost certainly benefit from alterations in the operating regime should the magnitude or persistence of streamflow change. The current operations are, in some sense, an artifact of historical experience. Management assumptions and the perception of risk are conditioned by recent hydrologic experience in the basin. An example of this is discussed by Dracup et al. (1985) in connection with the flooding experienced in the lower basin during 1983:

> The period of time that the Colorado reservoir system was filling constituted a period during which true exposure to climatic impacts, i.e. precipitation variability, did not exist.... The encroachment into the flood plain was possible because water was in storage upstream, and also because the period of filling Lake Powell was drawn out for almost two decades. Two decades are more than sufficient to affect societal perceptions of climate stability.

Water managers have traditionally relied upon the historical record in order to plan for the future, inferring the probability that shortages and floods might occur in the future from their frequency of occurrence in the past. If the existing record on the Colorado River is examined, however, it shows little ability to predict future conditions. The classic example of this is provided by the 20-year period immediately preceding the adoption of the Colorado River compact in 1922. During this period, average annual flows at Lee Ferry were approximately 17 maf/year, of which the Compact intended to allocate 16.5 maf/year. No period of similar duration and high flows has occurred since then, and the average flow at Lee Ferry from 1906 to 1990 has been only about 15 maf/year. Tree-ring analyses suggest that the long-term average flow may be as low as 13.5 maf/year and that the most critical period on record may have had a 20-year average flow of only 11 maf (Stockton and Jacoby, 1976). This illustrates the problem of relying exclusively on the recent instrumental record as a basis for planning, and suggests that any attempt to model future water supply will be hindered by such a reliance on historical data. The problems inherent in what is known as "critical period planning" have been discussed by many researchers (Loucks et al., 1981; Lettenmaier et al., 1984).

The problem of planning is compounded by the fact that we cannot even say with certainty whether runoff in the basin will increase or decrease. Most people with an interest in the basin have focused on the prospect of long-term decreases in runoff and the shortages that would result, which is a logical reflection of the region's preoccupation with drought. The fact that average temperatures in the region will almost certainly increase suggests that, if we assume no knowledge about changes in precipitation, we would expect runoff to decrease as a result of increases in evaporation and vegetative water use. In addition, most of the GCM temperature and precipitation scenarios modeled as part of this study suggest that runoff will decrease even though precipitation may increase, with runoff decreases ranging from 8 to 20 percent. This may be reason enough to plan for supply shortages; but increased water storage must be traded off against the need for flood control space. The greatest risk of climate change is the potential for streamflow variability to increase substantially, increasing the frequency of both sustained drought events and high-flow events.

Ultimately the problem is our ignorance of the underlying distribution that governs streamflow. Current operating procedures, although somewhat flexible, are strongly keyed to the existing historical record. When viewed from the perspective of climate change, the brevity of this historical record becomes an even greater concern. While a system certainly must be able to address historical variations and extremes to be effective over the long term, it must be able to address even greater variations that might reasonably be anticipated in the future. Scenarios derived from GCMs are useful in this respect because they provide additional information on changes in streamflow that might accompany climate changes. The problem of planning water management in the face of a high degree of climate and hydrologic uncertainty cannot be resolved easily; nonetheless, it should be possible to increase flexibility in water management, particularly if additional flexibility is incorporated into the legal and economic institutions, as well as into the technical and operational rules, that govern water use in the basin.

In addition to the uncertainty in future hydrology posed by climate changes, any change in hydrology may pose additional policy challenges for the region. As hydrology changes, it may well become more difficult to reconcile the claims of different users and multiple purposes along the river. Institutional and operational regimes will have to respond to tensions between the upper and lower basins, between demands for hydroelectricity and water supply, and between water supply and flood control.

Given the uncertainty surrounding potential climate changes and the problems encountered in trying to model impacts, care must be taken to view the results presented here in their appropriate context. While some analysts and planners, when faced with large uncertainties, may prefer to refrain from any attempt to assess the impact of climate change on water resources, the authors believe that it is preferable to see how far one can get using current information and models even though they might seem inadequate to the task. We can try to identify the weakest links in our current systems and to see what additional research is needed. The greatest danger, however, is that the numbers will be accepted uncritically when, in fact, they are bound by considerable uncertainty. Nevertheless, numbers may help us to represent and to comprehend the sensitivity of the basin to plausible scenarios of climate change. In particular, the scenarios of changes in temperature and precipitation derived from GCMs provide the best information currently available on climate change. A scenario need not be true in order to be useful. It is a guide to thinking about the future and may provide a sense of the difficult tradeoffs that the basin will face in the future. When translated into changes in runoff and water supply, as in this study, these climate scenarios suggest that past assumptions about water supply reliability may be severely challenged in the coming decades. By suggesting plausible future scenarios, we may find the impetus to consider what changes we can make to balance multiple purposes under varying conditions of climate. Because the past is likely to be a poor guide to the future, it is imperative that we consider how we can increase the resiliency of our existing water management systems and minimize the social and environmental impacts of changes in water availability. Models such as the NWSRFS and CRSS can be used in a creative manner to generate new scenarios, new strategies, and new ideas that may help us deal with future challenges. It is imperative that we move quickly to identify and test those responses that will provide us with the greatest flexibility in the coming decades.

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SENSITIVITY OF PACIFIC NORTHWEST WATER RESOURCES TO GLOBAL WARMING

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ABSTRACT

Although a long-term upward trend in the atmospheric concentration of carbon dioxide and other so-called greenhouse gases is well established, the effect of these changes on the land surface environment, including water resources, is less understood. Generally, there is some consistency in climate-model predictions that surface temperatures will increase, and that in many areas, precipitation, as well as evaporation, may increase as well. Determining the effects of such changes on land surface hydrology, and on the reservoir systems, remains problematic. This paper reports an assessment of the possible sensitivity to climate change on the American River, Washington. Long-term sequences of daily runoff were simulated by coupling a deterministic snow accumulation and ablation model with a topographically based soil moisture accounting model. Sensitivity to uniform increases in temperature of 2°C and 4°C was tested. For warmer climates, it was found that snow accumulation would be substantially reduced, and the high-flow season would shift from the spring to the winter. Potential evaporation would increase throughout the year (mostly in the summer), but peak actual evaporation would shift to the late spring and early summer due to reduced summer soil moisture.

The effect of the altered hydrology on hypothetical reservoirs of size 0.25 to 0.50 of the mean annual flow operated for minimum instream flow release (a surrogate for fisheries protection and enhancement), agricultural water supply (summer demand peak), and hydroelectric power generation was tested. Both an heuristic or rule-curve operation and an optimal operating rule were tested. The results showed that water supply reliability would be degraded significantly by a shift in the seasonal runoff pattern that would accompany warmer climates, given present precipitation. Hydroelectric revenues might increase due to larger releases during the winter peak demand season. Hydropower revenues were increased substantially through optimal operation for present climate. However, the optimal operation model could do little to mitigate the degradation in the system's water supply reliability for warmer climates.

CLIMATE CHANGE AND WATER RESOURCES MANAGEMENT: NOW THAT WE KNOW THE ISSUES--WHAT CAN WE DO?

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ABSTRACT

Changes in atmospheric chemistry during the last century have caused great concern regarding potential climate change and subsequent impacts on earth system processes. Theories and projections regarding the potential impacts on water resources and the sensitivity of specific geographical regions to these impacts are being discussed extensively. This paper summarizes these issues and then focuses on some of the options available to water resources managers. The paper discusses some basic policy questions that water resources managers need to consider and presents possible research, mitigation, and adaptation activities that can be undertaken at this time. The paper also presents some of the problems involved in implementing activities of this nature.

SUMMARY OF ISSUES

The earth's atmosphere consists of fixed proportions of oxygen, nitrogen, argon, and minute quantities of other gases. Although oxygen, nitrogen, and argon make up 99.9 percent of the atmosphere (excluding the widely varying content of water vapor), the remaining 0.1 percent play a critical role in the climate of the earth. These additional gases include carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide, and tropospheric ozone. These gases, plus water vapor, are commonly known as greenhouse gases because they trap heat in the atmosphere much like glass traps heat in a greenhouse. It is known that the chemical composition of these gases is not only changing, but at unprecedented rates.

Fossil fuel burning, world wide, emits about 5 billion tons of carbon into the atmosphere each year. Electric utilities produce 33 percent of the emissions, transportation 31 percent, and industry 24 percent. The destruction of forests adds to the problem by releasing the carbon stored in trees and by destroying a source of CO_2 consumption. Analyses of ice cores from Greenland and Antarctica show that the atmospheric concentration of CO_2 remained at 280 parts per million (ppm) for most of the last 10,000 years since the last Ice Age. Then in the late 18th century, the concentration began increasing exponentially from 280 ppm to the current concentration of 350 ppm (Lins et al., 1988). There is no question, after three decades of observation, that atmospheric CO_2 is rising at a rate that suggests about half of fossil fuel CO_2 is remaining airborne (Pearman, 1991).

Atmospheric concentrations of methane, CFCs, and nitrous oxide are also increasing. Methane is a relatively potent greenhouse gas produced by the digestive tracts of ruminant animals, animal wastes, swamps, flooded rice fields, fossil fuel production, landfills, and termite activity. The atmospheric increase in methane over the last decade is measured to be about 1 percent per year (Pearman, 1991). The increase in methane is attributed to increases in the number of ruminant animals and the increased acreage of rice fields and landfills. CFCs, which are usually associated with the destruction of stratospheric ozone, are man-made chemicals used as refrigerants, solvents, aerosol propellants, and blowing agents for insulations and plastic foams. CFCs are increasing in the atmosphere at a rate of 5 percent per year (Pearman, 1991). Although there is an international effort to eliminate the production of CFCs, they are trapped in existing products and will continue to be released into the atmosphere in the future. CFCs have an estimated atmospheric life of 100 years. Nitrous oxide, which is produced by biomass burning, fossil fuel consumption, crop residues, and nitrogen fertilizers, is currently increasing in the atmosphere at a rate of 0.3 percent per year (Pearman, 1991).

IMPACTS ON TEMPERATURE

The effect of increased concentrations of greenhouse gases on global temperature is uncertain. It is generally believed that increased greenhouse gases will trap additional heat in the atmosphere. This would lead to increased evaporation and evapotranspiration that, in turn, could lead to increased cloud cover. The net effect of increased cloud cover is uncertain since clouds play a dual role of both warming and cooling the earth. Clouds impede the escape of long-wave radiation from the surface of the earth to space, which results in a warming of the earth's atmosphere; however, they also scatter incoming solar radiation, which results in a cooling of the earth. Cloud type is also an important factor. High-level cirrus clouds tend to have a warming effect while low-level cumulus clouds tend to have a cooling effect (Graetz, 1991). Whether the net effect of increased cloudiness would be warming or cooling is unknown.

Another major uncertainty is the interaction between the ocean and the atmosphere. The ocean and the atmosphere exchange both energy (heat) and mass (CO_2 and other gases). The upper 3 meters of ocean have the same heat capacity as the entire atmosphere. When it is considered that the mean depth of the ocean is approximately 4 kilometers, the vast heat storage capacity of the ocean can be appreciated (Stanton, 1991). It is generally accepted that the ocean will absorb much of the excess CO_2 in the atmosphere and, if the atmosphere warms, much of the excess heat. It is known that major changes in atmospheric CO_2 levels accompanied the last Ice Age; however, it cannot be currently determined if CO_2 changes led or lagged behind the temperature changes. If current estimates of the sensitivity of global temperature to CO_2 levels are correct, then the CO_2 concentrations must have been directly related, in some manner, to the cooling or reheating of the planet (Pearman, 1991).

The present generation of general circulation models predicts that the planet will experience an average global warming in the range of 2°C to 5°C over the next 50 to 100 years (Lins et al., 1988). Temperature gauges show a warming trend over the last 100 years of approximately 0.6°C, although scientists attribute the warming to a number of different phenomena including the greenhouse effect, long-term natural trends, and increased sunflare activity. Although general circulation models are the best technology available for predicting future climate, the models need major improvements in how they handle cloud physics, ocean-atmosphere interactions, and vegetation. Given the current state of knowledge in atmospheric physics, ocean interactions, and climate modeling, climate predictions probably will not improve greatly for at least a decade.

IMPACTS ON WATER RESOURCES

Impacts of global climate change on water resources would result primarily from changes in temperature and precipitation, specifically changes in the type of precipitation (rain versus snow) and the quantity and distribution of precipitation. Changes in precipitation would cause changes in the magnitude and timing of runoff and the magnitude and frequency of floods and droughts. Changes in temperature would result in changes in evaporation and evapotranspiration, soil moisture, and infiltration. In coastal areas, the potential for sea-level rise and saltwater intrusion could also cause significant problems. It is important to keep in mind that climate change will not be geographically uniform and the differences from region to region will likely compound existing water resources problems.

Changes in temperature and precipitation could directly affect the demand for water and the availability of water supplies for agriculture, municipal and industrial uses, hydroelectric power generation, the environment, and recreation. Changes in temperature and precipitation could affect water quality, the spread of aquatic weeds, groundwater recharge, saltwater intrusion, and environmental assets such as wetlands and fisheries. Virtually every area of water resources management could be affected from basin management to reservoir operations to on-farm deliveries. Subsequent changes and impacts could occur in land use, types of crops, crop yield, water allocations, the economy, and the location of population centers.

Preliminary sensitivity studies have shown that an increase in average global temperature of 2°C to 4°C coupled with a change in precipitation of plus or minus 10 percent could result in a change in runoff between +35 and -50 percent in semi-arid river basins in the western United States (Gleick and Nash, 1991). In addition, the studies show a shift in the snowmelt runoff season of approximately 1 month earlier, with peak runoff occurring in May instead of June. This reflects the premise that under higher temperatures more precipitation falls as rain rather than snow and that snowmelt occurs earlier in the year. Initial studies also show some effects on flow variability.

POLICY QUESTIONS

Global climate change deals with two factors that the water resources community is very familiar with: probability and risk. When a new dam is planned and designed, the amount of flood protection provided depends on the probability that a major flood event will occur and the related risk of damages, loss of water supply, and loss of life. When a new structure is designed, the amount of protection provided depends on the probability of factors such as high wind, earthquake, and excessive loads and the risk of damages, loss of use, and loss of life that would result from a structural failure. Similarly, the amount of protection against the impacts of global climate change that should be provided depends on the probability that severe impacts will occur and the risk to water supplies and the economy that would result.

In the above examples, the magnitude of the consequences depends on the magnitude of the event. If very little global warming were to occur or global warming were to occur at a slow enough rate, then the water resources community would probably be able to adapt with very little advance planning. However, if global warming were to occur at the magnitude and rate predicted by the current climate models and the water resources community had not prepared, the consequences could be severe in terms of water shortages and economic and sociological impacts. In these examples there is always a tradeoff between the amount of resources that are initially allocated for protection and the amount of resources that are spent on the consequences if a major event occurs and protection was not provided. In most cases, the cost of protection is less than the cost of dealing with the consequences of a major destructive event.

The uncertainty, probability, and risk of dealing with the potential impacts of global climate change generates a whole new set of policy questions:

- Should the water resources community wait for a reduction in the uncertainty of global climate change or should it begin taking action to hedge against that uncertainty now?
- What actions should the water resources community take at this time to help prevent or minimize global warming and to prepare for the impacts of global warming that may occur?
- What level of resources should the water resources community initially invest for protection against the potential impacts of global climate change?
- How much risk should the water resources community take that severe impacts will not occur?
- What are the relative costs of different actions and what are the costs of not implementing these actions if severe impacts occur?

The water resources community needs to take a cautious but prudent path that balances the uncertainty of global climate change with the risk of severe impacts to water resources. It is also important to recognize that many of the concerns regarding the impacts of global climate change on water resources are the *same* concerns that will need to be addressed in the future due to population growth, full development of river basins, and severe sustained drought (specifically increased demands for water with reduced water supplies). This is important to note because much of the resources invested in climate-change research and development of responses and strategies should benefit other water resources management issues that are now occurring and will intensify in the future.

POLICY APPROACHES

There are basically five approaches to dealing with the problem of global climate change:

- Mitigation
- Adaptation
- Research and development
- A combination of the above
- No action

Mitigation employs policy options that eliminate or reduce greenhouse gas emissions and options that offset emissions by removing greenhouse gases from the atmosphere, by blocking incident solar radiation, or by altering the reflection or absorption properties of the earth's surface (NRC, 1991). Mitigation is an approach that maximizes protection against climate-change impacts and minimizes the risk of severe consequences. Since mitigation attacks the source of the problem, it can be effectively implemented without knowing what the magnitude or direction of the impacts will be. The primary benefit of mitigation is that the severity of impacts can be reduced before the impacts ever occur. The actions also have the potential for providing benefits such as reduced pollution, increased energy efficiencies, and new technologies. A risk in this approach is that mitigation actions must be implemented in advance of the onset of impacts and might require a large initial investment without fully knowing what the magnitude of the impacts might be without the actions.

Adaptation employs options that help human and ecological systems adjust or adapt to new climate conditions and events (NRC, 1991). Adaptation attacks the problem after the impacts have occurred. Although adaptation strategies and responses can be developed before impacts are fully known, adaptation cannot effectively be implemented until the direction and magnitude of the impacts are known or adequately predicted. The benefit in this approach is that the cost of adapting to climate-change is relative to the magnitude of impacts that actually occur. If the impacts of global warming are minimal, then very little adaptation and cost would be required. The risk in this approach is if the impacts are severe, adaptation could be very costly and difficult to achieve.

Research and development provides a better understanding of the overall science of global climate change, provides better predictions of what may occur, and prepares methods and tools to assist in adapting to the impacts of climate change. Research and development also provides the data and information necessary to make informed policy decisions regarding the type and magnitude of actions that need to be taken. Although research and development requires an initial investment without knowing whether the impacts will ever occur, much of the knowledge and tools developed will provide results applicable to other climate-change and water resources issues.

POSSIBLE ACTIONS

From an impacts perspective, mitigation is the best approach for dealing with potential global climate change. Mitigation would reduce or eliminate the problem at the source and would move the climate toward a no-change condition, regardless of the magnitude or direction of potential impacts. From an economic perspective, adaptation would be the best approach if the impacts were minimal. If the impacts were severe, a combination of mitigation and adaptation would probably be the best approach. From a sociological perspective, both mitigation and adaptation could cause personal inconvenience and hardships and require major changes in lifestyle. A combination of mitigation and adaptation would probably be the best approach for minimizing sociological impacts.

The following activities are mitigation actions that can be undertaken at this time. Most of these activities would require no additional resources and are prudent actions regardless of whether global warming occurs.

- Support the policies, initiatives, and legislation of the administration, federal agencies, Congress, and the private sector for reducing the greenhouse gas emissions.
- Support research by agencies and universities in reducing the greenhouse gas emissions by agriculture, livestock, wetlands, and others sources.
- Continue improving the efficiency of hydroelectric power generation facilities and develop new facilities where feasible and environmentally sound.
- Support research in the development and improvement of alternative energy sources such as solar power, wind power, geothermal, and nuclear.
- Develop programs to reduce greenhouse gas emissions through reduced transportation, energy consumption, and waste; fuel-efficient vehicles; and increased energy efficiency.

The following activities are research and development actions that can be undertaken at this time. Some of these activities prepare for future adaptation actions. Several of these activities would provide results applicable to other water resources issues.

- Gather and develop the information and technology necessary for understanding the relationships between climate change and hydrology and the potential effects on snowmelt, runoff, evaporation, runoff forecasting, droughts, floods, and groundwater recharge.
- Develop the models and tools necessary to determine the impacts of climate change on water resources and to assist in development and implementation of adaptation strategies.
- Determine the sensitivity of river basins and existing water projects to changes in water demands and water supplies. Determine the adequacy of existing water supplies, under projected climate-change scenarios, to meet present and anticipated water demands for agriculture, municipal and industrial uses, hydroelectric power generation, the environment, and recreation.
- Perform research on the potential impacts of climate change on environmental parameters such as water quality, the spread of aquatic weeds, fisheries, wetlands, and riparian communities.
- Determine the potential impacts of global climate change on water systems management and water project operations.

- Develop responses to the potential impacts of climate change through water conservation; and through improved efficiencies, water use methods, and water systems management and operations.

- Explore strategies and responses to increase existing water supplies or develop new water supplies when they are determined to be inadequate. Continue research and development of alternative sources of water such as cloud seeding, groundwater recharge, and desalinization.

- Develop and support real-time data gathering and real-time operations networks for monitoring the impacts of global climate change and for operating water systems under changed climate conditions.

- Begin addressing the potential impacts of global climate change in planning, design, environmental, and dam safety studies considering factors such as sea-level rise, increased evaporation, earlier runoff seasons, and extended growing seasons. Determine if global climate change will affect procedures such as the computation of probable maximum floods and reservoir sizing.

- Investigate the limitations of existing water laws and institutions to adapt and respond to climate change. Investigate the potential effects on the priorities of competing demands, water allocation methods, project purposes and priorities, and water sales and transfers.

IMPLEMENTATION

Research and development activities have been implemented by almost every scientific, natural resources, and policy-related agency in the United States, most universities and research organizations, and many private companies. The global change research programs of federal agencies fall under the U.S. Global Change Research Program, a presidential initiative to establish the scientific basis for national and international policy-making related to natural and human-induced changes in the global system. The program was developed by the Office of Science and Technology Policy; Federal Coordinating Council for Science, Engineering, and Technology; Committee on Earth and Environmental Sciences. The need for full agency participation is stated in the U.S. Global Change Research Program FY 1991 Research Plan as follows: "The U.S. Global Change Research Program must be viewed as a single integrated research effort where its success is dependent upon cooperation and contributions from each of the individual agency programs."

The success of the U.S. Global Change Research Program clearly depends on the ability of the individual agencies to develop, implement, and fund global-change research. Since the program does not provide additional funds to accomplish this research, agencies must obtain these funds from existing appropriations and funding sources or develop entirely new sources. If agencies are to prepare adequately for the uncertainties of global climate change and the impacts on water resources, it is essential that adequate funding be provided. However, given the current federal budget climate and existing agency priorities, workloads, and commitments, this will be difficult to accomplish.

Mitigation activities have been much slower to develop. Mitigation activities must be implemented by the private sector, federal government, and society as a whole. Ideally, the free market system will drive effective mitigation activities; however, if this system is not successful government regulation may be required. Education and voluntary compliance will be critical factors in the success of mitigation activities.

CONCLUSIONS

The tremendous amount of greenhouse gases that are being emitted into the atmosphere by mankind will undoubtedly force some kind of change in the earth's natural processes, including the earth's climate. Although the magnitude and even the direction of those changes are uncertain, severe impacts probably will occur. If this probability is to be reduced or eliminated, it is imperative that immediate action be taken.

Water resources managers, as well as the rest of society, need to adopt and implement a combination approach involving research and development, mitigation, and adaptation. Research and development is a critical first step because it can help reduce the uncertainty in climate-change predictions and can help define the best balance of mitigation and adaptation for different probabilities of impacts and different levels of risk. While research and development is occurring, mitigation should be implemented in those areas that are least expensive to achieve and that provide other benefits such as reduced pollution, increased energy efficiencies, and new technologies.

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SOUTHEAST REGIONAL SENSITIVITY TO CLIMATE CHANGE

Joel B. Smith, Chairperson
Cory W. Berish, Ph.D., Rapporteur

On November 5, 1991, presentations by Drs. William S. Cooter, Barbara Miller, John Schaake, Jurgen Schmandt, and Daniel Sheer illustrated the potential sensitivity of the southeast United States to changes in water quantity and quality associated with changing climate conditions. Based on real-life drought conditions, such as the drought of 1988, water quality and quantity in the Southeast could be significantly impacted if future climate conditions resemble those that existed in 1988, especially if the conditions exist over the entire Southeast and for an extended temporal period.

The speakers indicated that general circulation models (GCMs) have significant limitations for detailed regional projects. The session participants agreed that mesoscale models will be very useful in the future. At present, regional mesoscale models nestled with GCMs are not widely available or refined to a level useful for water managers. The lack of available modeling tools is a barrier to effective planning for potential future conditions.

The speakers indicated that many project-level studies and water management models are very useful "now" to understand water resources sensitivities. For example, Dr. Schaake indicated that simple models, such as his elasticity model, are useful for understanding how changes in precipitation, potential evapotranspiration, and runoff are intimately linked through the driving process of solar energy and ambient air surface temperatures. Similarly, Dr. Miller presented research from the TVA area that supported the conclusion that it is very important to quantify and understand water system parameters to predict potential hydrologic sensitivities to changes in ambient climate conditions.

In the TVA system, the drought of 1988 provided a basis to study "hot-dry" conditions that could occur as the result of global climate change. As ambient air temperature increases, Miller found that about 50 percent of ambient temperature change is reflected in surface-water temperature within the TVA system. Higher surface-water temperatures could negatively impact the entire Southeast. Higher surface-water temperatures reduce power generating equipment efficiency, the cooling efficiency of water, and in extreme cases can actually close nuclear electric power generating plants as per NRC safety regulations.

All of the speakers suggested that water systems can be classified as to their sensitivity to changing climate conditions. Shallow, shadeless, and slow-moving streams are especially at risk to increases in air and therefore, water temperatures and/or to decreases in streamflow. Damage to aquatic systems can be acute if surface temperature is high and large amounts of oxygen-demanding materials are present. High levels of BOD materials can reduce dissolved oxygen concentrations below a critical concentration of 5 to 6 parts per million.

Drs. Schmandt and Sheer highlighted the fact that water systems designated for multiple use will probably have water use allocations changed in future years. For example, Dr. Sheer pointed out that traditional water management for Lake Lanier in Georgia has been for power production, recreation use, and flood control. Drinking-water supplies for the population of the greater Atlanta area were covered even though they were not explicitly planned for as part of the multiple water use of Lake Lanier. However, given the rapid development along the Chattahoochee River, future water allocations may be driven by the need for drinking water and for adequate fresh-water input into the Gulf of Mexico to maintain traditional Gulf fisheries. Dr. Schmandt pointed out that many systems in arid areas face the same multiple-use problems as the Chattahoochee system, but that the problems are exacerbated by the hot and arid climate. For example, along the arid border of Texas and Mexico, the Rio Grande River is already stressed by rapid urban and agricultural development. Any change in water availability--driven by changing climate conditions--will severely stress the natural resources and human population dependent on the Rio Grande system.

The presenters discussed potential future directions of water management research in relation to changing climate conditions. One common thread among the speakers was the need to understand ecological function; for example, what are the functional parameters that govern the way a particular stream or water system functions? Such delineations may be especially important for coastal systems where future sea-level rise may flood wetlands, reduce aquifer recharge, contaminate drinking-water (groundwater) supplies, and reduce fisheries reproduction potential. Following parameter delineation, information transfer to practical water systems managers is especially important.

CLIMATE CHANGE AND WATER RESOURCES INTEGRITY OF INLAND STREAMS SUBJECT TO MUNICIPAL POINT-SOURCE IMPACTS

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ABSTRACT

The biological integrity of inland streams reflects an interplay of factors commonly grouped into five major categories: (1) chemical factors (including water temperatures and pollutant loadings); (2) biotic factors (species composition and interrelationships); (3) energy sources (solar radiation and organic matter such as leaf litter); (4) physical habitat features (streambank or channel condition and riparian vegetation); and (5) the flow regime. Climate change could affect such variables as water temperatures and flows. In particular, elevated summer water temperatures combined with potential reductions in warm-season flows could clearly stress aquatic ecosystems. Predicting regional changes resulting from climate-related stressors can become complicated for relatively unpolluted (natural) waters since the impacts may vary for different types of organisms and biotic community structures. The task is simpler when streams receive loadings from municipal point-source discharges. Assimilating the organic materials and ammonia depletes instream dissolved oxygen. Increased water temperatures further increase the magnitude of these lowered oxygen levels. If instream dissolved oxygen concentrations fall much below 5 milligrams per litre (mg/l) during summer high temperature and critical low-flow conditions, then major adverse impacts to biotic and general water quality conditions would be anticipated.

Wasteload allocation modeling techniques allow predictions of water quality impacts associated with regional climate-change scenarios. The results of such model predictions for the southern United States indicate potential water temperature increases in excess of 5°C. To avoid severe oxygen depletion impacts, municipal discharges to all but the largest streams would likely require some type of advanced waste-water treatment. Wherever possible, promoting the establishment of riparian tree-cover to provide a shading level of at least 50 percent could further mitigate the impacts and often allow for less stringent levels of advanced treatment. Ideas for further research are noted, including more detailed evaluations of the potential costs of facility upgrades.

INTRODUCTION

The idea of estimating the impact of climate change on stream water quality had its beginnings in a project dealing with crop production (Cooter, 1990). This initial study focused on the potential impacts of climate change on corn in the southern United States. As part of the study, a crop-production model was linked to the EPA PRIZM model to predict edge-of-field and groundwater infiltration losses for nitrates and pesticides. Impacts on crop yields showed mixed results, with climate change making some areas in the Southeast an even more attractive place to grow nonirrigated corn. On the other hand, there was a strong suggestion that, depending on the location, climate change might increase the rates of nutrient and pesticide losses to either ground or surface water. This led to the idea of examining the possible impacts of climate change on water quality using approaches that focused more directly on what was going on *in the water* (Cooter and Cooter, 1990).

In the initial crop-production study, a large number of assumptions were needed to fit information from the climate models into the other models growing the crop and moving pollutants to the edge of the field or through the soil profile to the groundwater. Both the corn model and PRIZM were detailed simulation models. They are set up to use data inputs from weather events of fairly short durations (e.g., daily values). The data inputs are expected over a long stretch of time, for all seasons, and for all types of weather. They are also "field-level" models and need data inputs geared to specific locations.

Many researchers are hesitant to apply general circulation model (GCM) results to small regions (Grotch, 1988), where "small" means something about the size of a typical state. These climate models are also better at predicting air temperatures than cloud cover and rainfall patterns. When the search began for an approach with a more solid water quality thrust, the best course of action seemed to be to concentrate on "fair weather" model outputs.

Obvious candidates were high-summer conditions centered on July or August. This time of the year automatically focuses on the types of predictions the climate models are best equipped to make. For most of the country, this time of the year also constitutes a period of lowest streamflows and maximum instream water temperatures. The high-summer period generally presents a set of critical conditions for maintaining key water quality factors. In particular, the summer is the period when streams usually show the lowest levels of dissolved oxygen, the saturation level of which is inversely related to water temperature. Dissolved oxygen levels will be further depressed if a stream receives appreciable inputs of waste-water discharges. Microorganisms break down organic materials and ammonia from the discharges. This eventually leads to the assimilation of the wastes, but this self-purification consumes oxygen, and the rate of oxygen consumption increases as the water temperature increases (Velz, 1984; Thomann and Mueller, 1987).

If one's environmental science training includes wasteload allocation modeling and sanitary engineering, the idea of approaching global warming as a variant of a familiar type of water temperature sensitivity analysis seems quite logical. In fact, when this idea first presented itself, it seemed the literature would already reflect studies along these lines. A few general references turned up (Gleick, 1989; Jacoby, 1989; and more recently Jacoby, 1990; Scott et al., 1990), along with some studies dealing with lakes (Blumberg and Di Toro, 1990; Miller and Brock, 1989). But no one seemed to have applied readily available engineering models for wasteload assimilation in streams to quantify the impacts of global-change phenomena on water temperatures and water quality.

Focusing on streams, and further concentrating on streams receiving appreciable input of treated waste water, is attractive for several reasons. In the first place, it allows the range of water quality factors to be narrowed to a handful of strategic variables. In a "natural" stream, overall water quality integrity is related to at least five major types of features (Karr et al., 1986). As summarized in Figure 1, these features include the flow regime, water quality and water chemistry, biotic factors, the sources of energy (food and nutrients), and the condition of the stream habitat.

Water temperature, which is the variable we will be most interested in, falls under the major category of water quality and water chemistry as does another important variable, dissolved oxygen. Temperature and dissolved oxygen are important variables for any stream, but in most natural waters, temperatures must increase fairly dramatically before temperature by itself would adversely impact overall water resources integrity. For instance, even for water temperatures around 40°C, natural streams with low levels of organic loadings can usually maintain average diurnal dissolved oxygen levels above 6 mg/l (APHA, 1985). Dissolved oxygen levels at or above 5 mg/l are desirable to support an ecologically healthy population of fish (U.S. EPA, 1976 and 1986).

Climate change has the potential to affect a number of factors related to water quality integrity. Climate change might alter the basic flow regimes or lead to shifts in riparian vegetation and other habitat features. Suitably complex models could attempt to describe this more complicated set of interactions. But adding these extra levels of complexity requires more information. Where there is uncertainty regarding the needed extra data inputs, the

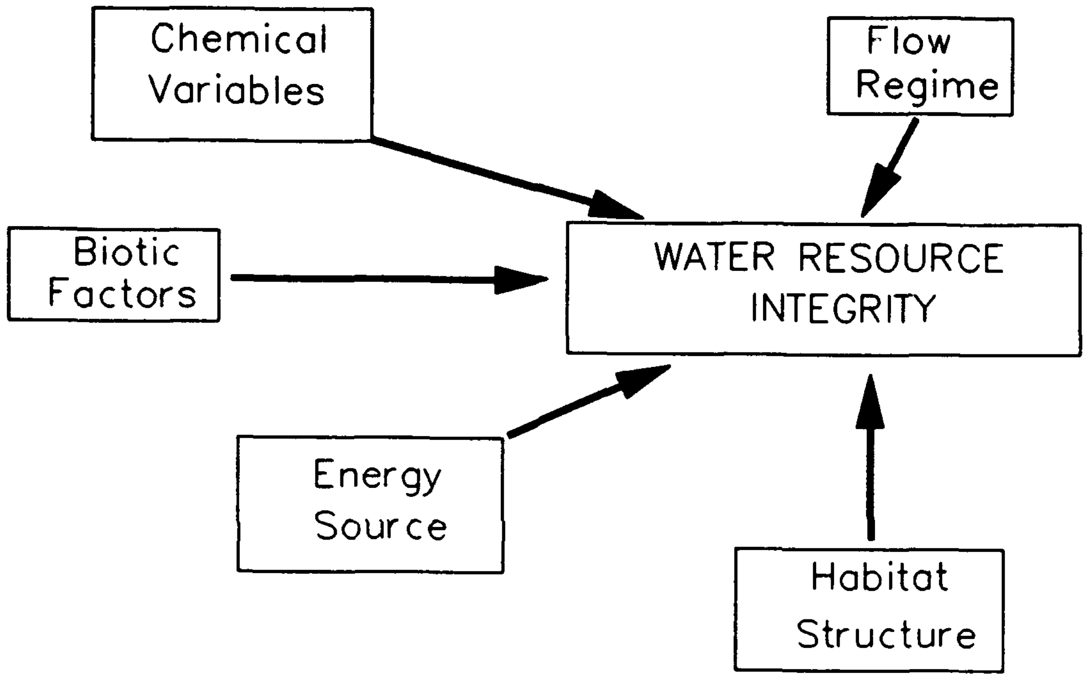

Figure 1. **Five major classes of environmental factors that affect aquatic biota (adapted from Karr et al., 1986).**

model predictions will also be uncertain. The conclusion is that modeling natural systems can easily become quite complicated. By the same token, modeling a system under stress can help simplify the analysis. A stream carrying a significant load of organic wastes falls into the category of a stressed system. Fairly simple modeling approaches can help decide whether the waste load is large enough to drive the dissolved oxygen appreciably below the level of 5 mg/l (Leo et al., 1984). If this happens, major adverse impacts can be expected for the stream's fishery resource and its overall biological integrity. An increase in water temperatures can only make things worse. The idea, therefore, is to examine situations where climate change and possible increases in water temperatures could add enough stress to a stream to push the dissolved oxygen levels below a tolerable standard like 5 mg/l under summer low-flow and critical high-temperature conditions.

In addition to focusing the analysis on a critical set of factors affecting dissolved oxygen concentration, the decision to study systems under stress encourages the consideration of policy options. The major reason the stream is stressed has to do with anthropogenic impacts; that is, the stream carries an appreciable loading of treated effluent. Climate change leading to increased water temperature increases the stress, but the policy option of increasing the degree of waste-water treatment can always be investigated. In addition, so long as the stream is not too large, trees along the shoreline can create dense shading over a large portion of the water surface. Blocking out 50 percent or more of the high-summer incoming solar radiation can mitigate a large portion of potential climate-change impacts. Taking steps to preserve or augment stands of trees along riparian corridors downstream of waste-water discharges is another policy option worth considering.

From the points outlined above, the main steps involved in our analysis of climate change impacts to stream systems in the southern United States can be summarized readily. The output from three GCMs was combined with other climatological data to carry out calculations on possible changes in water temperatures associated with a doubling of greenhouse gases. A set of circumstances was defined representative of commonly encountered types of discharges of municipal waste water for small to intermediate-sized streams. The implications were considered of varying the stringency of waste-water treatment. The benefits of streambank shading were also evaluated. These main points will now be covered in greater detail. The overall results will be summarized and some concluding remarks will suggest areas of research worth additional consideration.

POSSIBLE CLIMATE-CHANGE IMPACTS ON WATER TEMPERATURES

The outputs from three climate models were examined (Cooter and Cooter, 1990). These included the Goddard Institute of Space Studies (GISS) model, Princeton's General Fluid Dynamics Laboratory (GFDL) model, and the Oregon State University (OSU) model. For each model a series of grid boxes that are the basic spatial units for model estimates were selected to approximate the southern United States. These grid-box areas are shown in Figure 2. Climate-model outputs are available for each grid-box centroid.

None of these models predict surface-water temperatures directly, but all three models provide the information to generate such estimates using empirical equations based on well-established thermodynamic principles. There are a number of versions of the same general approach (Velz, 1984; Theurer, 1984; Sullivan et al., 1990). The variant I used was taken from a readily available EPA technical guidance manual (Mills et al., 1982, based on Edinger and Geyer, 1965). This equation calculates an average daily surface-water temperature from a set of inputs including the daily average air temperature, the amount of solar radiation reaching the water, and extra factors depending on the relative humidity, cloud cover, and wind speed. The only terms that cannot be taken directly from the climate models have to do with the solar radiation reaching the water surface. On the open oceans or over very wide rivers, lakes, and estuaries, no shading factors are needed. But for inland waters, it can be important to factor in the impacts of shading from large trees in the riparian zone. If all the trees have been removed, then once again, no shading factors are needed. For most of the southern United States, however, good-sized trees can be grown, and even a narrow buffer zone of such large trees along the banks of a stream can intercept 50 percent or more of the incoming solar radiation.

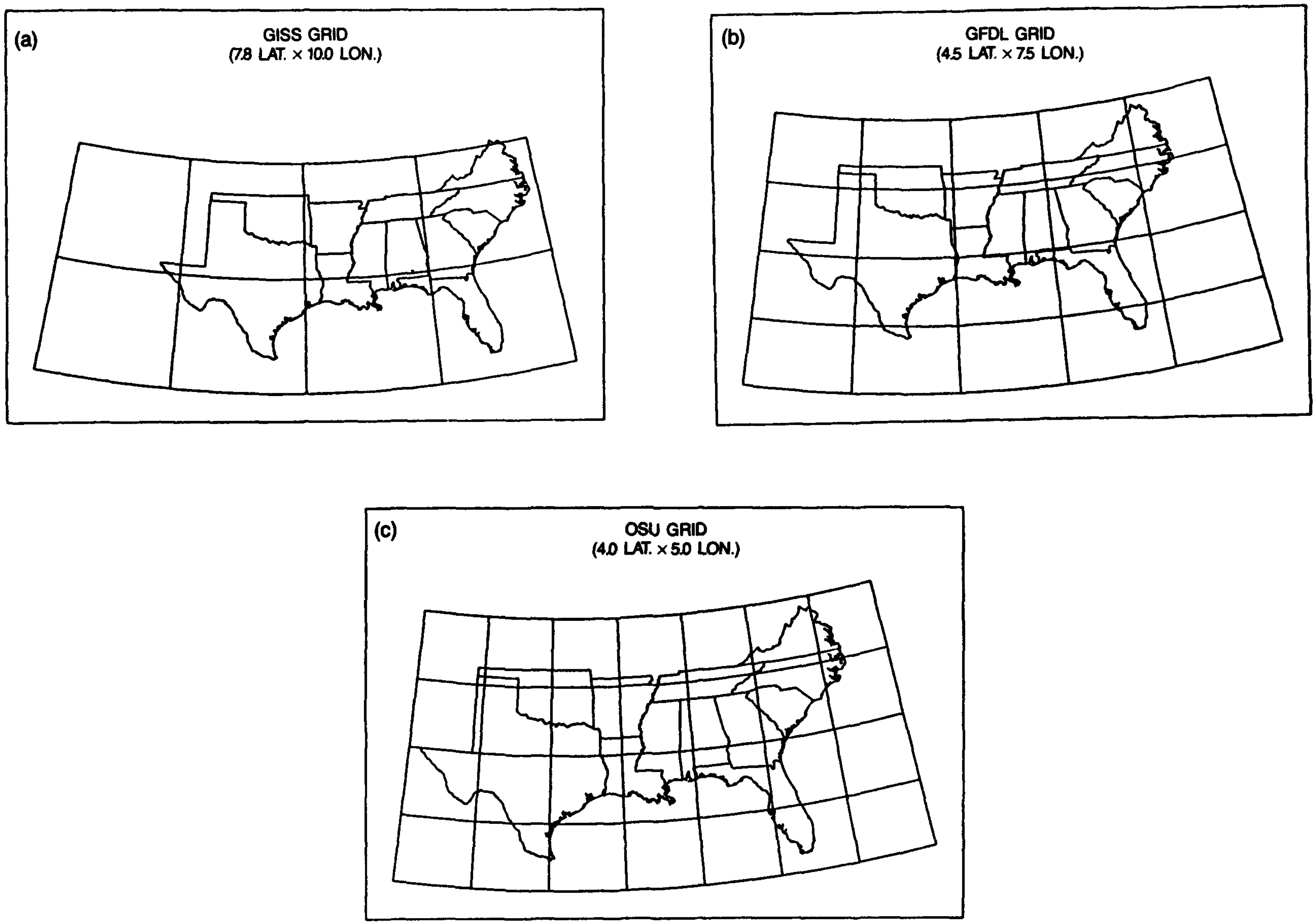

Figure 2. **Horizontal resolution of three general circulation models (GCMs) across the southern United States: (a) GISS, (b) GFDL, and (c) OSU.**

Working from data based on climatological norms equivalent to the variables the climate models generate, it became apparent that some degree of shading was needed for the water temperature predictions to match patterns based on long-term averages from actual water temperature measurements (Geraghty et al., 1973, Plate 10). Since no statistics are available on riparian timber conditions and the associated shading effects, some reasonable assumptions were needed. Based on the types of riparian tree species likely to be encountered under present climate conditions (OSDA, 1981), the southern United States was divided into three main zones. One region was west of about 97° W longitude (including most of Oklahoma and Texas). For the remaining territory (which might be thought of as the *southeastern* United States), a plausible ecological divide was identified at about 34° N latitude (approximately along the route of I.H. 40), with typical timber heights to the south of this line being slightly greater than in the region to the north.

To relate the height of the trees to shading, some assumptions were necessary on the size of the streams. A stream width of 15 meters was finally selected. This would accommodate most headwater-to-intermediate-sized streams. It would leave out large alluvial streams and estuarine and tidal rivers in coastal areas. This seemed justifiable since the next stage in the analysis, the wasteload allocation modeling, would be most useful on such intermediate-sized streams. Based on the use of this "typical" 15-meter-wide stream, Table 1 summarizes the potential high-summer shading effects. Water temperatures were then calculated from real data based on long-term climatological norms. The results showed a distribution pattern that matched reasonably well with the general pattern of high-summer measurements of average water temperatures.

As an alternative to using trees typical under current climate conditions, the literature on the potential effects of climate change on the species composition of forests in the southern and eastern United States was reviewed (Winjum and Neilson, 1989; Andrasko and Wells, 1989; and more recently Joyce et al., 1990). A reasonable working hypothesis was that the heights in the region of the southeast to the north of 34° N latitude might increase to about the same sizes as currently encountered in the zone to the south of this line. Tree heights for the other two regions were held constant. This provides another set of shading assumptions for use in the climate-change scenarios. Shading effects from the types of trees typical under present climate can be extrapolated into the future, or some slight alterations based on likely changes in forest compositions can be examined.

A series of contour maps was then prepared showing the temperature change patterns. In each map set, the baseline configuration based on current conditions appears to the upper left of the figure. Predictions based on the three climate models are then represented as changes from the baseline. The results are summarized in Figures 3 through 5. Figure 3 is *not* water temperature: it is ambient air temperature and is included to emphasize that the patterns for water temperatures are quite different. Figure 4 shows the estimated impacts on water temperatures from a doubling of greenhouse gases using shading factors based on present riparian tree species heights. Figure 5 gives estimates based on likely changes in riparian tree heights reflecting forest response to the new climate conditions.

As can be seen, the three different climate models give slightly different predictions. The Goddard and GFDL (Princeton) models are fairly similar as regards water temperatures, especially for the southeastern United States. The Oregon model stands out as somewhat different. On the other hand, for air temperatures, the Oregon model marches closely in step with the Goddard model, with the GFDL model being a bit different. These results are mainly due to the ways the model predictions of air temperatures interact with other model outputs for humidities (mixing ratios) and wind speeds.

Since the models give different predictions, it is counterproductive to focus on single numbers. It is better to look at overall patterns and ranges. On this basis, it is obvious that all the models suggest that climate change could lead to an increase in water temperatures ranging from 1°C or 2°C up to a fairly impressive 7°C or 8°C. The next stage in the analysis is to see what these sorts of water temperature changes could mean for a typical stream in the southern United States receiving an appreciable waste-water discharge. This introduces the wasteload allocation modeling techniques.

Table 1.

Representative Riparian Species of the Southeastern United States

LOCATION	MATURE HEIGHT	REPRESENTATIVE SPECIES	% SHADING OF 15 M STREAM
West of 97°W Longitude	7 meters	*Celtis reticulata* (Netleaf Hackberry) *Cephalanthus occidentalis* (Buttonbush) *Fraxinus pennsylvanica* (Green Ash) *Sapindus drummondii* (Western Soapberry)	28%
East of 97°W Longitude North of 34°N Latitude	18 meters	*Carya cordiformis* (Bitternut Hickory) *Carya glabra* (Pignut Hickory) *Quercus alba* (White Oak) *Quercus macrocarpa* (Bur Oak) *Quercus rubra* (Northern Red Oak)	62%
East of 97°W Longitude South of 34°N Latitude	24 meters	*Celtis laevigata* (Hackberry) *Pinus glabra* (Spruce Pine) *Quercus falcata* (Southern Red Oak) *Quercus laurifolia* (Swamp Laurel Oak) *Quercus michauxii* (Swamp Chestnut Oak) *Quercus nigra* (Water Oak) *Taxodium spp.* (Cypresses)	84%

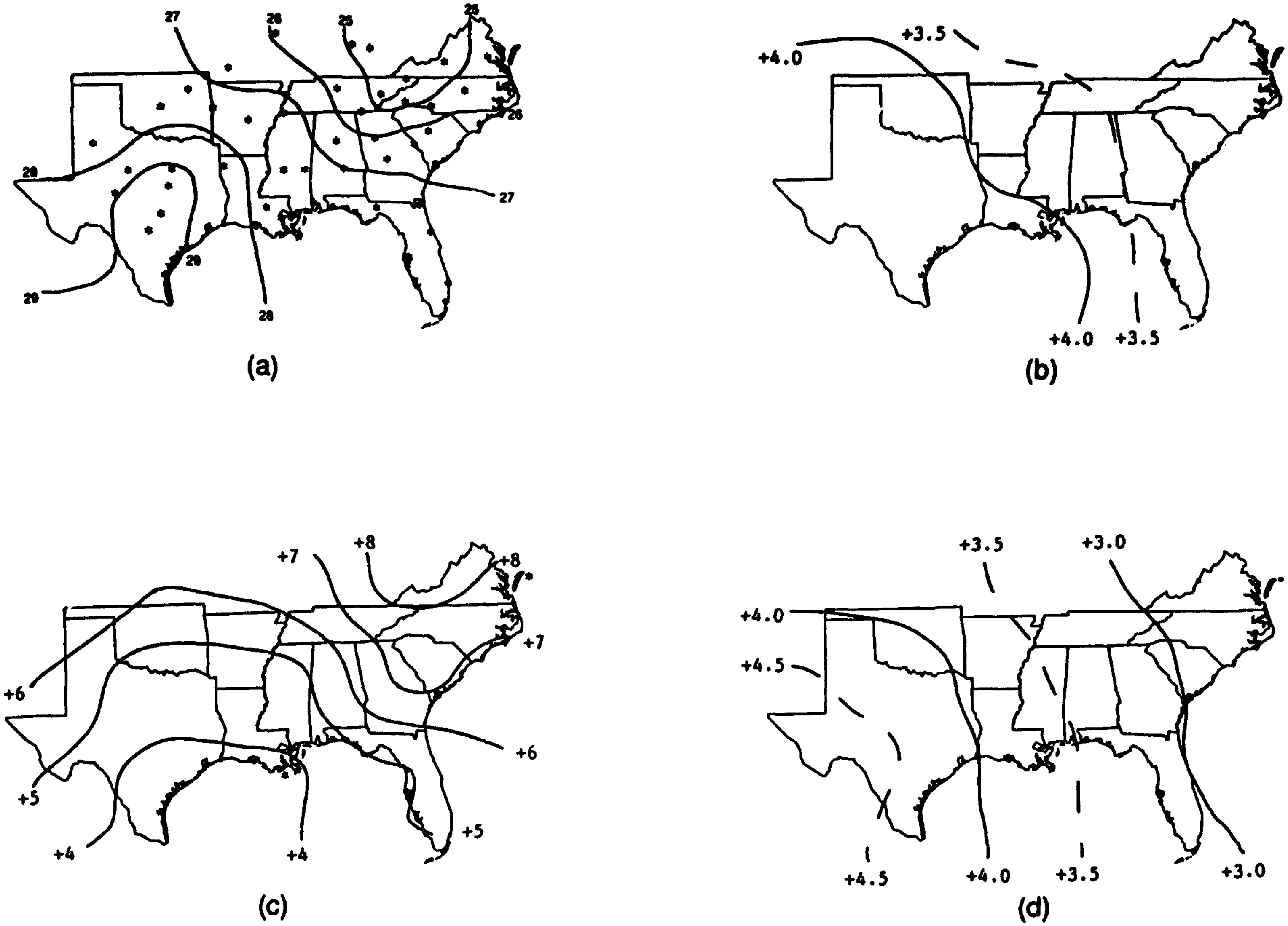

Figure 3. **Thirty-year mean July air temperatures and changes from mean July GCM base air temperatures resulting from doubled atmospheric CO_2 (C degrees): (a) historical base, (b) GISS, (c) GFDL, and (d) OSU.**

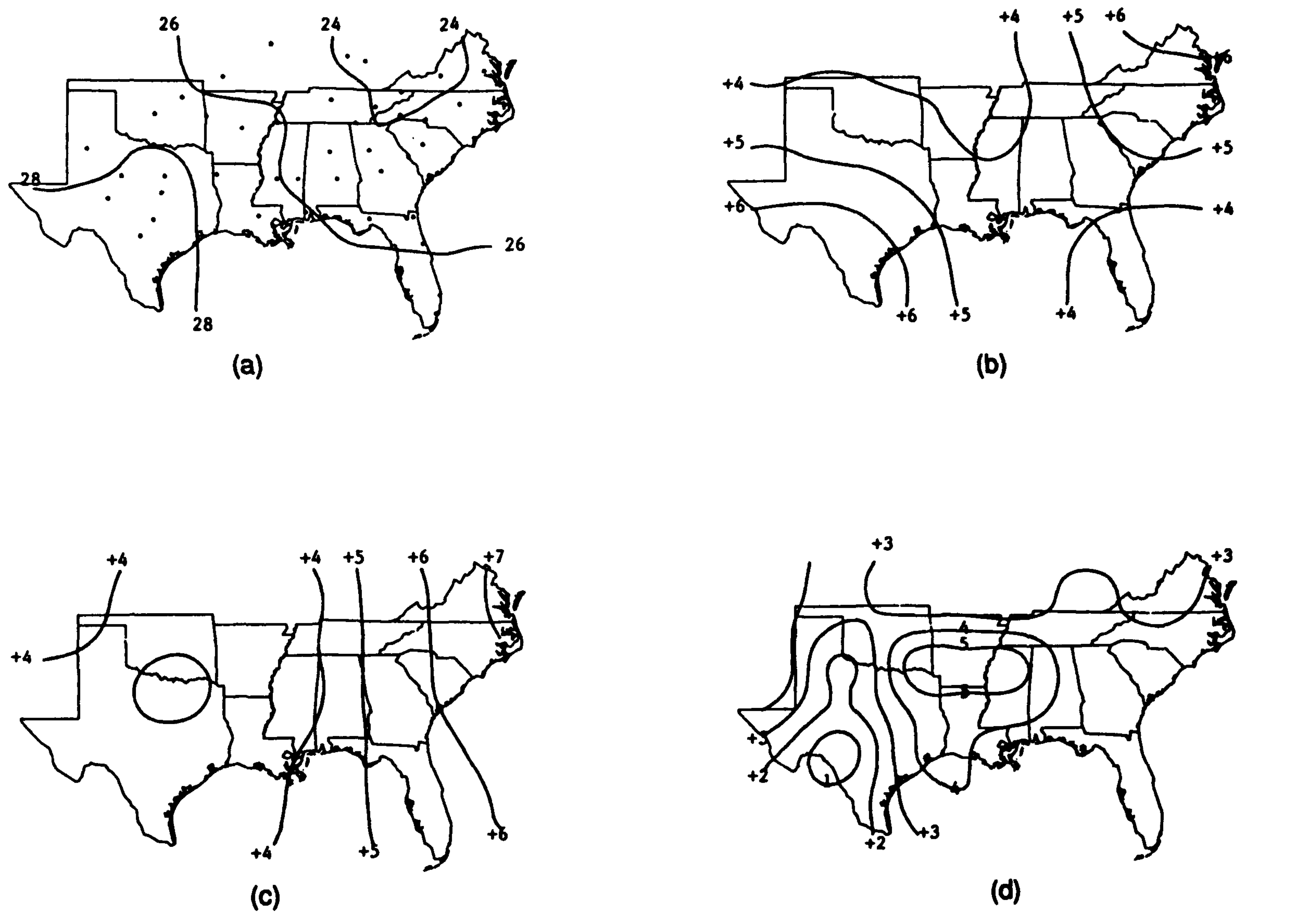

Figure 4. **Historical mean July equilibrium surface–water temperatures and changes from computed GCM base water temperatures resulting from doubled atmospheric CO_2 (C degrees): (a) historical base, (b) GISS, (c) GFDL, and (d) OSU.**

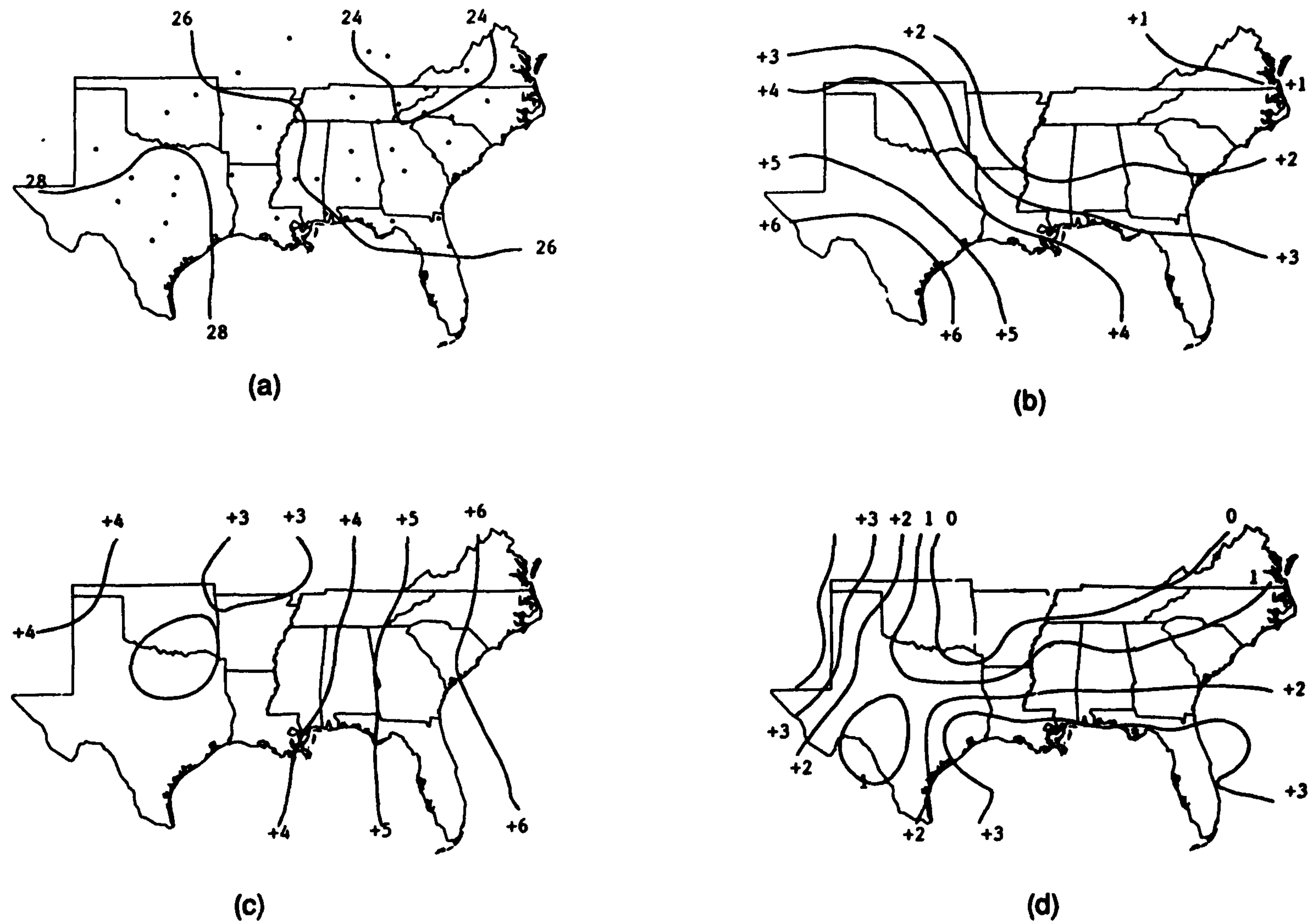

Figure 5. **Historical mean July equilibrium surface-water temperatures and changes from computed GCM base water temperatures resulting from doubled atmospheric CO_2 and postulated southern forest migration (C degrees): (a) historical base, (b) GISS, (c) GFDL, and (d) OSU.**

ESTIMATING THE IMPACTS OF WASTE-WATER DISCHARGES

The total study area covers 12 states, each of which has anywhere from several hundred to several thousand permitted municipal dischargers. Attempting to provide a detailed evaluation of the potential impacts of climate change on all these dischargers would be a challenging undertaking. Given the large size of the study area and the inherent uncertainties in site-specific predictions stemming from the different climate models, a simplified screening analysis was performed based on a typical discharge situation for a small to intermediate-sized stream system.

Since the focus is on streams under some appreciable degree of stress from the waste-water inputs, a set of specifications was selected where the stream could be carrying around a third of its flow derived from treated effluent. The extreme case of an intermittent stream could also be considered where the flow above the discharge point falls to zero and the stream below the discharge becomes effluent dominated. Using wasteload allocation modeling techniques, the degree of treatment stringency for the effluent could be varied to estimate the impacts on dissolved oxygen. These estimates can be performed over a range of different water temperatures.

As noted previously, a natural, unpolluted stream should easily be able to maintain a dissolved oxygen concentration well over 5 mg/l even with water temperatures in excess of 35°C (or greater than about 95°F). If a discharge introduces waste materials containing carbonaceous organics and ammonia, microorganisms will assimilate the wastes but in the process will consume oxygen. Reaeration will replenish the dissolved oxygen supplies, but if the discharge is large enough or concentrated enough, reaeration may lag behind consumption. This produces a pattern called the dissolved oxygen (DO) sag curve (Velz, 1984; Haslam, 1990). This is illustrated in Figure 6, where the concentration of the introduced wastes (measured as biochemical oxygen demand, or BOD) steadily decreases while the dissolved oxygen levels at first "sag," then rebound farther downstream.

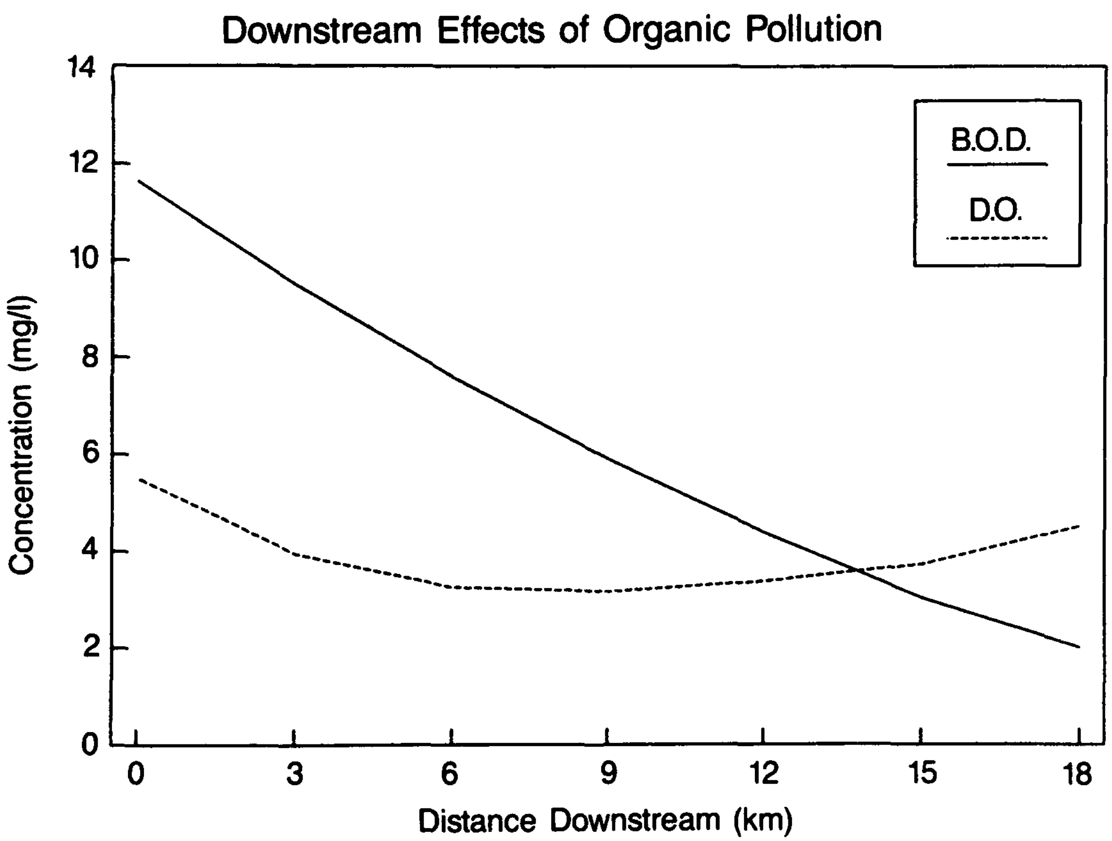

Figure 6. **Hypothetical dissolved oxygen sag curve.**

Wasteload allocation models help quantify the basic processes underlying the DO sag curve using a set of differential equations based on first-order kinetics (Velz, 1984; Thomann and Mueller, 1987; Zison et al., 1978). There are a set of reaction rates for the decay of the carbonaceous wastes and the ammonia, both of which consume oxygen. Reaeration is simulated using another reaction coefficient. The amount of flow in the stream and its velocity is specified. The loading from the discharger is added, and the model generates estimates of the instream dissolved oxygen levels moving downstream. The point where the dissolved oxygen reaches its minimum is often called the "sag point." If the dissolved oxygen at this minimum level is still above a level close to 5 mg/l, then stress on the stream from the discharge should not lead to serious impacts on the aquatic community. If the DO levels fall appreciably below 5 mg/l, then options should be considered to mitigate the situation. The most obvious course of action is to increase the stringency of waste-water treatment. As the organic and ammonia loadings to the stream are trimmed back, a wasteload threshold is reached where the sag point DO level falls safely above the required target.

The reaction coefficients in the wasteload allocation model are adjusted using a set of multipliers called Arrhenius correction factors. In general, the reactions proceed faster as the temperature is increased. Literature values for the rate coefficients are usually reported at a base temperature of 20°C. These base rates are then adjusted to match the conditions for a particular stream under critical high-summer water temperatures. These Arrhenius factor adjustments obviously lend themselves to an evaluation of the impacts of climate change. If climate change increases the water temperature, then the reaction rates will increase. This can affect the level of treatment recommended for the effluent. One of the implications of climate change is that more sophisticated levels of waste-water treatment might be required in the southern United States.

The minimum level of waste-water treatment is called secondary treatment (U.S. EPA, 1979). Greater levels of stringency become "advanced" treatment. Typical permit values at these two levels of treatment were considered for a hypothetical stream with the characteristics summarized in Table 2. Figure 7 shows the performance of the secondary treatment options over a range of water temperatures. Figure 8 takes a fairly high water temperature and shows the contrast between ordinary secondary treatment and advanced waste-water treatment. Figure 8 also shows what might happen on an intermittent stream (i.e., no flow above the discharge point) with a discharge using advanced treatment technology.

From Figure 7, it is apparent that secondary treatment would likely suffice where diurnal mean water temperatures are not much in excess of 25°C. From the global climate model predictions summarized in Figures 4 and 5, all the models suggest that the mean diurnal water temperatures could exceed 25°C under high-summer conditions, with water temperatures rising to around 30°C or more for some parts of the study area. That is around 90°F and, for a diurnal average, is fairly warm water.

Under these conditions, treatment more stringent than secondary would likely be needed to maintain a dissolved oxygen level at or above 5 mg/l. From Figure 8, advanced treatment technology could probably maintain the desired DO levels even at water temperatures around 40°C, or around 104°F. Even if the normal base flow were to disappear, advanced treatment could come very close to maintaining the 5 mg/l standard.

CONCLUSIONS

From the preceding analysis, the general conclusion is that advanced waste-water treatment could maintain adequate dissolved oxygen levels on small to intermediate-sized streams in the southern United States under climate conditions associated with a doubling in greenhouse gases. This is provided, of course, that the streams are allowed as much bank shading as possible. If the streams are stripped of large trees in the riparian zone, then the potential water temperature increases could inch even higher. Figure 9 shows the general relation between the percentage of bank shading and water temperatures for a site from the western end of the study area based on the EPA water

Table 2.

Wasteload Allocation Characteristics for a Sample Stream in the Southern United States

Carbonaceous BOD Decay Rate: 1.252/day (at 20°C) Arrhenius Factor: 1.047 Ammonia Nitrification Rate: 1.083/day (at 20°C) Arrhenius Factor: 1.083 Reaeration Rate: 5.943/day (at 20°C) Arrhenius Factor: 1.020 Stream Velocity: 2 feet/second (52.8 km/day)		
	EFFLUENT	HEADWATER
DISSOLVED OXYGEN (mg/l)	5.0	7.0
FLOW (MGD)	5.0	10.0
BOD5 (mg/l)	20 (or 5)	1.0
NH_3 (mg/l)	20 (or 2)	0.1

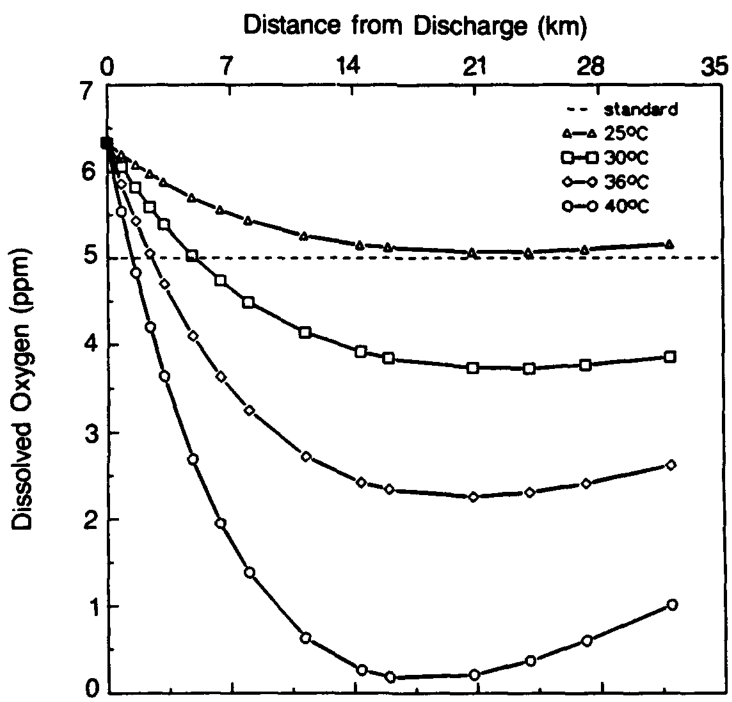

Figure 7. **Impact of water temperature on dissolved oxygen assuming a secondary level of water treatment.**

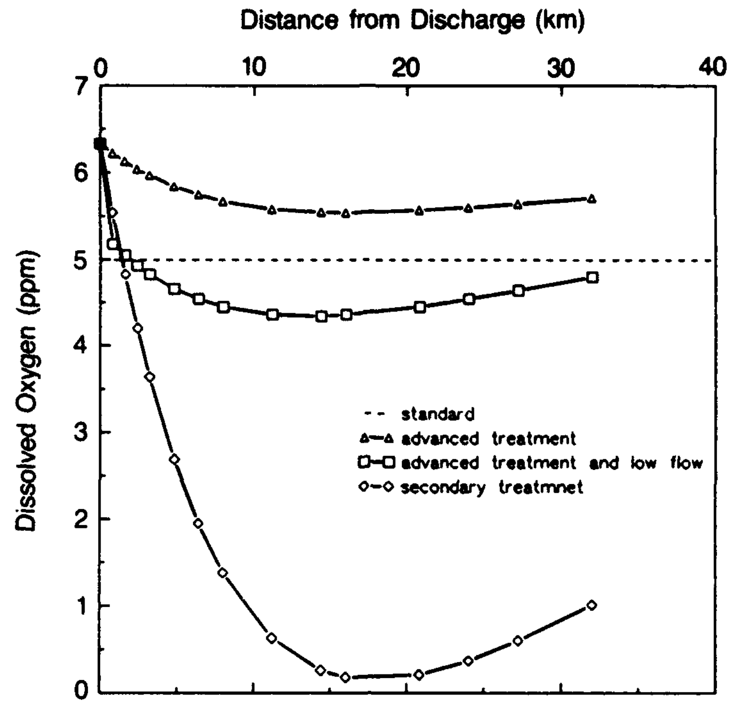

Figure 8. **Effect of treatment and flow and dissolved oxygen under elevated water temperatures (40 °C).**

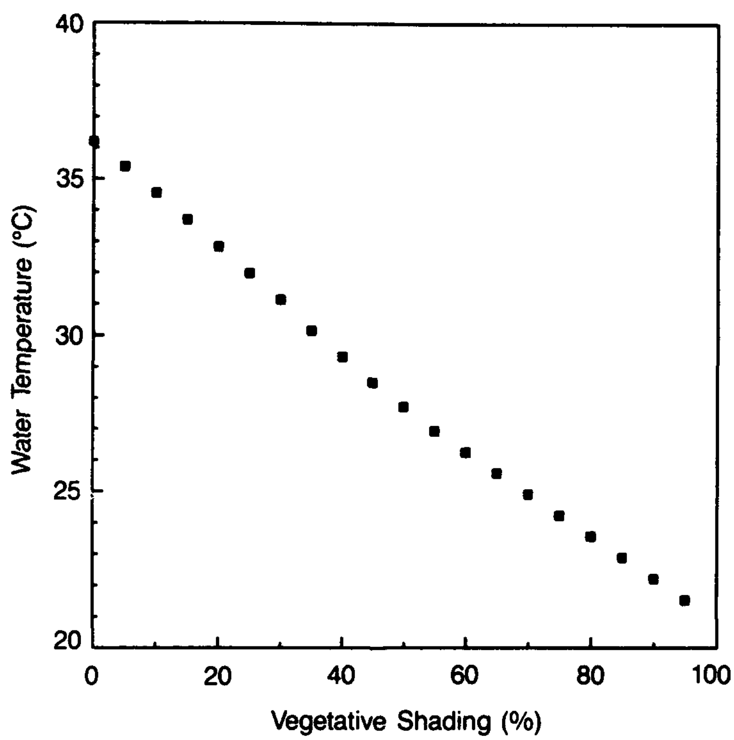

Figure 9. **Sensitivity of computed equilibrium water temperature to vegetative shading.**

temperature equation. For different sites, the absolute numbers would change, but the relative magnitudes would be very similar. Figure 9 shows that if a sizable dent is made in the shading, say, a reduction of 40 to 50 percent, then the water temperatures will increase by something close to 10°C. These types of predicted changes track very well with actual measurements of stream temperature changes taken in various parts of the country connected with logging practices that can remove riparian timber (U.S. EPA, 1973; Brown, 1970; Swift and Messer, 1971; Lee and Samuel, 1976; Erman, 1977; Hewlett and Fortson, 1982; Betschta and Taylor, 1988; Marcus et al., 1990; Sullivan et al., 1990).

For the southern United States, the effect on water temperatures of a doubling in the greenhouse gas levels would be more or less equivalent to removing most of the existing riparian tree cover under current climate conditions. Actually eliminating most of the bank shading under the doubled CO_2 climate scenario would in essence be a double blow to the water temperature regime. Without the bank shading, temperatures would rise even higher. In some parts of the southern United States, the water temperature increases might be around 10°C. This would yield diurnal average temperatures in the 40°C (100°F) neighborhood. At that point, even stringent advanced waste- water treatment technology would be hard pressed to maintain desirable levels of dissolved oxygen. And at these types of water temperatures, only a handful of hardy fish species could be expected to survive (U.S. EPA, 1976; Kennedy and Mihursky, 1967; Carlander, 1977; Lee et al., 1980; Meisner, 1990).

In terms of policy-related issues, the findings outlined above certainly encourage efforts to preserve riparian habitats and promote the establishment of stands of large-tree species to provide as much bank shading as possible. Even if the climate does not change to match the scenario of a doubling of greenhouse gases, this type of policy is worth considering. Even under current climate conditions, promoting bank shading in areas around point-source discharges might actually reduce the costs of waste-water treatment. If climate changes come to pass along the lines of the model predictions, the southern United States could certainly use every possible bit of bank shading.

The other model implication is that if climate change becomes a reality, then baseline secondary treatment for municipal waste-water discharges may become hard to justify over most of the southern United States. Some sort of advanced treatment would likely be necessary to maintain adequate instream dissolved oxygen levels. A promising area for followup studies would be to target a specific portion of the study area; for instance, a particular state like South Carolina, and perform some screening analyses on whether more stringent levels of treatment might be necessary in the face of increasing water temperatures due to climate change. Focusing on a more restricted area could also allow more detailed attention to the interactions with bank-shading effects. This sort of study would yield some cost estimates of potential climate-change impacts that would be very useful for policy studies. These techniques could be extended throughout the entire region. In time, similar analyses could be undertaken for other parts of the country.

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SENSITIVITY OF THE TVA RESERVOIR AND POWER SUPPLY SYSTEMS TO CHANGES IN METEOROLOGY

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ABSTRACT

To evaluate the sensitivity of the TVA reservoir and power supply systems to extreme meteorology, a series of models was used to quantify the relationship between changes in air temperature, water temperature, and thermal power plant performance. Within the Tennessee River system, for each 1°F increase in air temperature, water temperatures are generally increased by 0.25°F to 0.50°F. Increased air and water temperatures can cause reductions in power generation. Generation losses result from plant deratings, cooling tower usage, and/or nuclear plant shutdowns to avoid noncompliance with environmental and safety regulatory constraints, as well as from reductions in efficiency and other operational constraints encountered at high temperatures.

INTRODUCTION

During the record 1980s drought in the Southeast, multiple-use pressures in the TVA reservoir system intensified. The dependence of power generation on reservoir operations also became readily apparent. Due to low lake levels, the TVA power system had to compete with other reservoir uses for available flows to generate hydropower and to support thermal power generation. As a consequence of this experience, as well as to address potential climate-change issues, a multi-year study was initiated to assess the impacts of extreme meteorology on the TVA reservoir and power supply systems (Miller et al., 1992). The project objective was to gain an improved understanding of the interactions between hydrometeorology, reservoir operations, and power generation. Major phases of the project included (1) sensitivity analysis of individual system components to changes in hydrometeorology and (2) scenario analysis of the integrated system response to regional climate-change scenarios. This paper summarizes results from the first-phase sensitivity analysis.

THE TVA SYSTEM

The Tennessee River basin drains a 105,960-square-kilometer (40,910-square-mile) area from seven states in the southeastern United States. Within the river basin, TVA is responsible for a range of programs including power production, water resources management, economic development, and resource conservation. The TVA reservoir system, which includes 42 major dams and reservoirs, is a large multi-purpose system. Primary objectives are to provide for navigation, flood control, hydropower generation, recreation, and minimum flows for the maintenance of water quality and aquatic habitat. The reservoir system also supports fossil and nuclear power production by providing condenser cooling water and dissipating thermal wasteloads.

The TVA power system, one of the largest in the United States, has an installed capacity in service of approximately 28,000 megawatts (MW). In 1990, generation was provided by a combination of coal-fired (62 percent), hydroelectric (20 percent), nuclear (9 percent, with one operational nuclear plant), and combustion turbine (9 percent) facilities. The 1990 net generation from TVA's facilities totaled 115.6 million megawatt-hours (MWh), producing total operating revenues of more than $5.3 billion.

THE SIGNIFICANCE OF THERMAL ISSUES TO POWER PRODUCTION

Air and water temperatures influence environmental and safety compliance at thermal (fossil and nuclear) power plants, as well as the efficiency of power plant operations. At open-cycle thermal plants, water from the river system is used to remove waste heat from the condenser and then discharged back into the river. Environmental regulatory limits determine the maximum temperature of the effluent based on discharge temperatures and/or instream temperatures (such as a maximum downstream limit). In addition, the Nuclear Regulatory Commission (NRC) sets safety limits at the nuclear plants on the maximum temperature of intake water to the essential auxiliary and emergency cooling systems that provide backup cooling for support equipment and remove reactor heat during emergencies.

When cooling water intake temperatures are high, power plants curtail power production (derate) from full power output or use cooling towers (if available) to reduce the temperature of the discharge water and avoid noncompliance with thermal limits. If nuclear safety intake temperatures reach their limits, the plants must shut down. Consequently, elevated water temperatures can influence power generation by causing forced deratings, additional use of cooling towers, and/or nuclear plant shutdowns. Reservoir operations can also be impacted if additional flow releases are required to help moderate water temperatures for compliance purposes.

Increased air and water temperatures can also influence the efficient operation of electric power plants and cooling towers. Increased condenser cooling water temperatures reduce the efficiency of the power production cycle. Reduced power output can also result from internal mechanical and/or operational constraints encountered at higher ambient temperatures. Examples include maximum reactor power (nuclear plants), maximum coal feed rate (fossil plants), and maximum turbine backpressure. At higher temperatures, the reduced density of hot air can also influence the efficiency of air-draft systems, adversely impacting the combustion process at coal-fired plan.

At power plants operating in recirculating (closed-mode) cycle, cooling tower performance determines the temperature of the water entering the condenser. In the "wet" cooling towers used at TVA plants, evaporative cooling is facilitated by bringing hot water in direct contact with cooler, dryer air. Hotter, more humid air is less receptive to evaporation. Consequently, increases in air temperature and/or humidity can reduce the efficiency of cooling tower performance, thereby causing higher condenser inlet water temperatures and reduced power output.

The overall effect of changes in temperature on plant performance is illustrated in Figure 1. Reductions in power output are generally small over a wide range of intake temperatures. To maintain constant power output, however, fuel consumption must increase to offset reductions in efficiency. Temperature impacts become more apparent at higher temperatures--in the 70°F to 90°F range for TVA plants--as equipment and operating constraints become limiting and/or environmental constraints are reached. The slope of the curve can change abruptly--or reach a "knee"--at these critical points. The exact shape of the curve and location of the knee varies with plant design and the stringency of environmental and safety limits. This project quantifies the magnitude of these types of temperature-induced load reductions for representative TVA power plants.

SENSITIVITY TO INCREMENTAL CHANGES IN METEOROLOGY

Objectives and Methodology

A series of analyses were conducted to determine the sensitivity of the TVA reservoir and power supply systems to incremental changes in meteorology. The studies focused on five major components that influence the thermal response of the reservoir system and/or affect power generation: (1) dam release temperatures; (2) river system temperatures; (3) environmental compliance and safety issues; (4) power plant performance; (5) hydropower generation and reservoir operations; and (6) transmission. Results from components 1 through 4 are summarized in this paper.

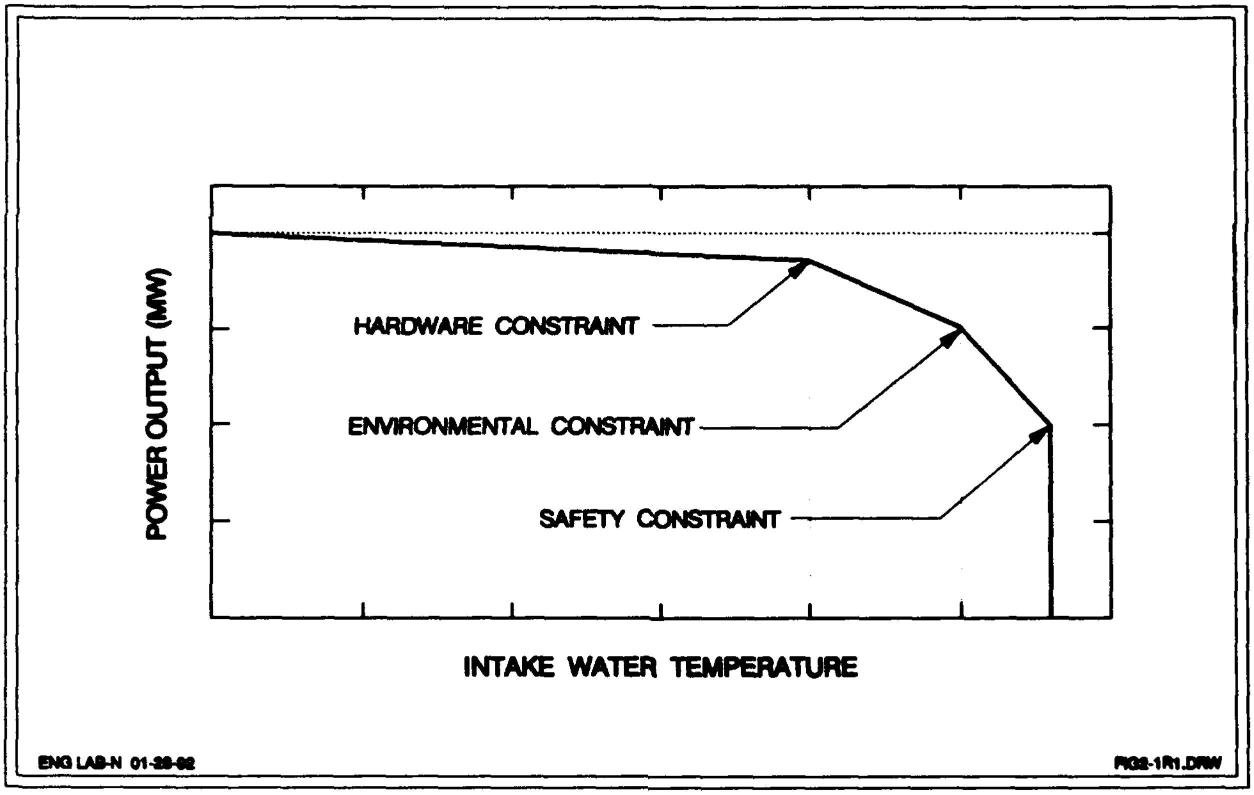

Figure 1. **Typical effect of water temperature on power output.**

The objectives of the analyses were to determine the following for each component: (1) the dominant meteorological variables that control thermal response, (2) the impacts of incremental changes in meteorology, and/or (3) critical response thresholds. The sensitivity studies were conducted using single-variable analysis techniques on representative average and extreme weather conditions and on representative sites. The meteorological variable of interest was uniformly incremented over a specified range, while other variables were held constant at their historical values. The years analyzed represent a range of flow conditions to implicitly account for hydrologic influences.

Based on natural flow and air temperature deviations from long-term mean conditions at Chickamauga Reservoir in Chattanooga, Tennessee, for the April through October period, the three selected years included 1974 (extreme cold-wet), 1965 (mean), and 1986 (extreme hot-dry). April through October represents the summer warming period when thermal stresses in the TVA system are most critical. In 1974 average air temperatures were 3°F colder and flows 25 percent wetter than the mean, while conditions in 1986 were about 2°F warmer and 60 percent drier than normal. Average air temperature and flow in 1965 approximate the long-term mean values of 70°F and 24,200 cubic feet per second (cfs), respectively. The extreme years were used to illustrate sensitivities beyond historical conditions, while the average year provided a basis for comparison.

It was assumed in the analysis that historical reservoir operations remained constant; current environmental and safety regulatory constraints were in effect; and Watts Bar, Sequoyah, and Browns Ferry nuclear plants were operational. Historical dam release temperatures were used to simulate the river-system water temperatures. Estimated water temperatures were based on well-mixed conditions, and the effects of stratification on power plant intake temperatures were not considered.

While these analyses are useful for identifying critical thresholds and evaluating the resiliency of the reservoir and power supply systems to meteorological variation, the methodology has limitations. Single-variable analysis on individual components ignores interrelationships between meteorological variables, as well as between reservoir and power operations. As historical conditions were uniformly incremented, the effects of seasonal shifts could not be accounted for. Use of representative years and sites may mask unique phenomena and precludes a probabilistic analysis of results. Variance of current thermal regulatory constraints and/or changes in reservoir operations could mitigate the simulated impacts.

Dam Release Temperatures

COMPONENT OVERVIEW

The effects of incremental changes in meteorology and inflow temperature on dam release temperatures were evaluated in this component for three typical reservoirs: a deep tributary (Norris), a transition tributary (Cherokee), and a mainstem reservoir (Chickamauga). Variables considered included dry-bulb temperature, dew point, wind speed, cloud cover, solar radiation, and inflow water temperature. A one-dimensional thermal model was used to model Norris Reservoir, while two-dimensional water quality models were applied on Cherokee and Chickamauga reservoirs (TVA, 1973; Hauser et al., 1987; Butkus et al., 1990). Model results are summarized as the average (April through October) deviation in dam release temperatures from base-case conditions.

RESULTS

At Norris, Cherokee, and Chickamauga reservoirs changes in air temperature and solar radiation had more significant effect on dam release temperatures than other modeled variables. Based on results from Norris Reservoir, wind and cloud cover also influenced average release temperatures; while changes in dewpoint temperature had an insignificant impact. In addition, water inflow temperatures significantly impacted dam release temperatures. Coupled changes in air and inflow temperature at Norris almost doubled the effect of changes in air temperature alone, indicating the importance of the boundary inflow water temperature conditions.

As shown in Figure 2, on the tributary reservoirs of Norris and Cherokee, approximately 25 percent of the air temperature deviation was reflected in the release temperature (a 2°F increase in air temperature results in a 0.5°F increase in release temperature). The impact on the mainstem reservoir, Chickamauga, was slightly greater, where on the average almost 40 percent of the air temperature deviation was translated into changes in release temperature. Wind effects were also greater on Chickamauga than on the other modeled reservoirs.

Differences in the thermal response of the three reservoirs can be attributed to differences in reservoir type and operation. Chickamauga has the largest surface area of the three reservoirs. It also experiences more convective mixing and less stratification due to a larger throughflow; consequently, it appears more sensitive to meteorological influences. Norris and Cherokee are tributary reservoirs that remain more strongly stratified through the summer; water temperatures below the thermocline appear to be less sensitive to meteorological influences.

A comparison of base-case condition release temperatures illustrates the importance of hydrology and reservoir operations on release temperatures at the tributary dams. At Norris and Cherokee, the warmest release temperatures occur in the cold-wet year, while the coolest occur during the hot-dry year. Under wet conditions, high-flow releases typically flush out the cool hypolimnic water early in the year, producing higher summer release temperatures. Conversely, in a dry year, flow releases are minimized and the cooler water below the thermocline is conserved later into the year.

No critical-response thresholds were identified. Changes in air temperature, air+inflow water temperature, solar radiation, and dewpoint temperature were related directly to changes in release temperature; while changes in wind speed and cloud cover were inversely related.

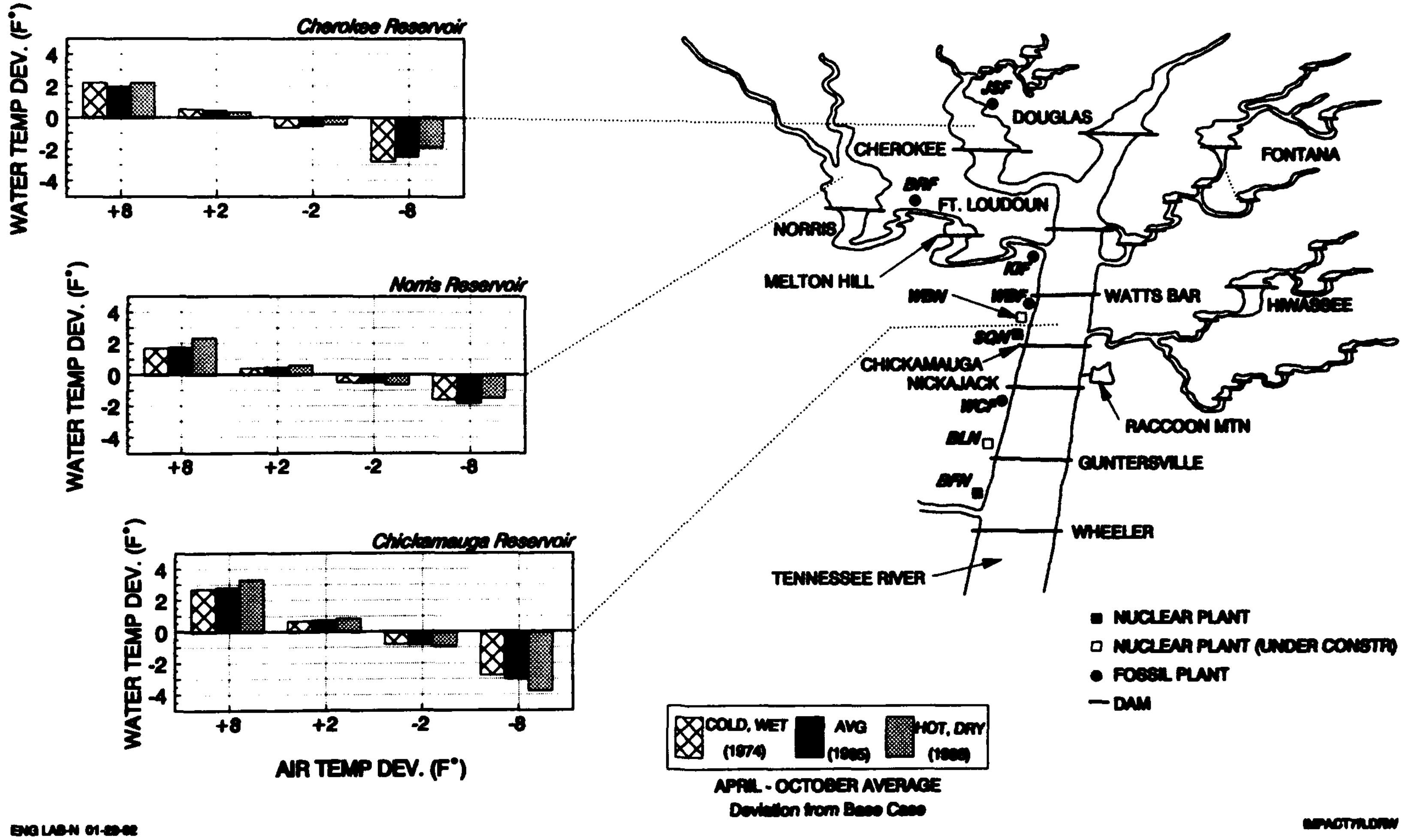

Figure 2. Impact of changes in air temperature on dam release temperature.

River System Temperatures

COMPONENT OVERVIEW

The impacts of incremental changes in selected meteorological variables on well-mixed river water temperatures were evaluated in this component. SYSTEMP, a one-dimensional mathematical model capable of simulating flow dynamics and thermal processes, was used to compute longitudinal temperature distributions in the upper Tennessee and Clinch rivers (Alavian and Ostrowski, 1992). Meteorological variables considered included air temperature, wind speed, and solar radiation. SYSTEMP model results were analyzed at those reservoir/riverine reaches that supply cooling water at four selected TVA power plants: Bull Run Fossil Plant (BRF), Kingston Fossil Plant (KIF), Watts Bar Nuclear Plant (WBN), and Sequoyah Nuclear Plant (SQN). Results are summarized as the average deviation of water temperature from base conditions for the April through October period.

RESULTS

The dominant variables that influenced thermal response of river-system water temperature were air temperature and solar radiation. Incremental changes in air temperature were directly related to changes in (well-mixed) water temperature, and no critical thresholds were apparent.

The cascading influence of reservoir operations and meteorology on water temperature down the reservoir system is illustrated in Figure 3. Moving downstream from Norris Dam, in an average year (1965), for each 1°F increase in air temperature, water temperatures increased by 0.10, 0.30, 0.33, and 0.38°F for the April through October period at Bull Run, Kingston, Watts Bar, and Sequoyah power plants, respectively. Water temperatures at Bull Run were influenced largely by the temperature of Norris Dam releases, which were relatively cool. Farther downstream on the Clinch River and mainstem of the Tennessee River, meteorological effects became more pronounced, with the greatest impact apparent in Chickamauga Reservoir.

The impact of increased air temperatures appeared to be greatest in a hot-dry year and less evident in a cold-wet year; thermal response in a mean year falls between the two extremes. In Chickamauga Reservoir near Sequoyah Nuclear Plant, under the most extreme conditions (1986, T+8°F), almost 50 percent of the change in air temperature was reflected in water temperature deviations (+0.47°F Twater per +1.0°F Tair). This represents as much as a 1°F greater incremental impact in the hot year 1986 than the cool year 1974.

Environmental Compliance and Safety Issues

COMPONENT OVERVIEW

The impact of incremental changes in water temperature on the ability of fossil and nuclear power plants to meet environmental and safety limits was evaluated in this component. Simplified thermal environmental compliance and safety water intake models were applied to five representative fossil plants and three nuclear plants in the Tennessee and Cumberland River basins. Model results are presented in terms of days exceeding discharge/ instream limits, days of required cooling tower use or plant shutdown, and/or days of equivalent load reductions for each year.

At the four plants on the upper Tennessee River (Bull Run, Kingston, Watts Bar, and Sequoyah), expected water temperature deviations resulting from incremental increases in air temperature were based on the SYSTEMP model runs. At the remaining plants on the lower Tennessee River and Cumberland River (Browns Ferry, Widows Creek, Colbert, and Cumberland), SYSTEMP simulated model results were not available. Increases of +2°F and +4°F were applied to historical water intake temperatures to approximate the effects of +4°F and +8°F increases in air temperature.

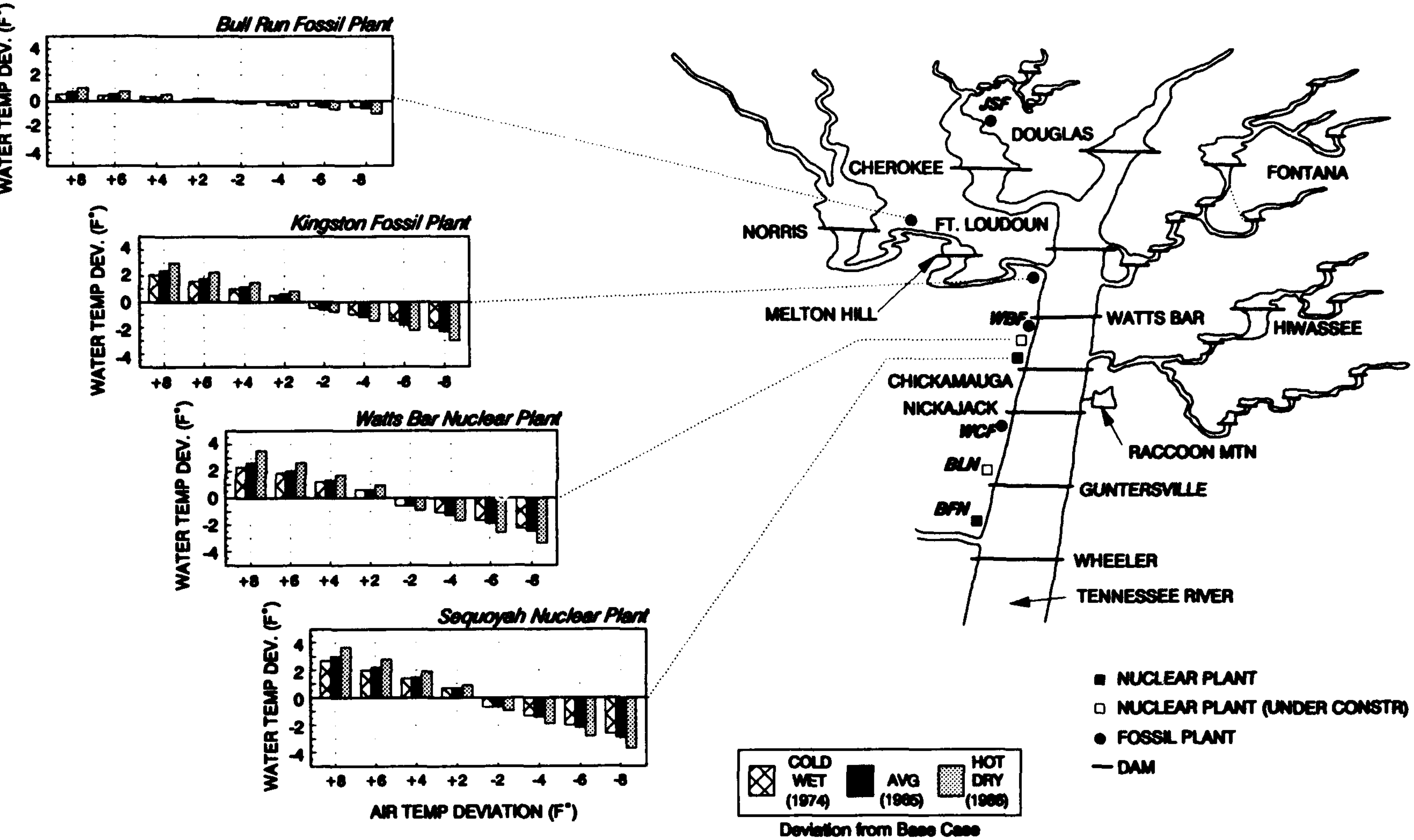

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Figure 3. Impact of changes in air temperature on water temperature in the upper Tennessee River.

Environmental Compliance and Safety Issues

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RESULTS

Increased air temperatures and associated water temperatures can increase the incidences of exceeding environmental and safety intake limits at thermal power plants in the TVA system. The impacts, however, are plant specific, depending on the location of the plant, the stringency of the thermal limits, and the type of year.

In this analysis, warmer temperatures did not influence environmental compliance at Kingston Fossil or safety compliance at Watts Bar Nuclear Plant. Exceedence of thermal limits at Kingston was avoided under base-case and simulated conditions due to the relatively high discharge limit at the plant, coupled with cool-water releases from Norris Reservoir. Similarly, the safety intake limit at Watts Bar Nuclear Plant was not exceeded under base-case or increased temperature conditions.

Under current (base-case) climate conditions, Sequoyah Nuclear, Widows Creek Fossil, and Cumberland Fossil did not exceed thermal limits. Bull Run Fossil, Browns Ferry Nuclear, and Colbert Fossil plants were, however, subject to thermal limit violations. Bull Run thermal compliance was influenced largely by Norris Dam release temperatures. Assuming full plant operation, discharge limits were exceeded from 4 to 7 days in the wet to mean years (1974 and 1965). The high-flow releases in these years flushed the cold water from the reservoir early in the year, producing relatively high release temperatures late in the summer. At Browns Ferry and Colbert, environmental compliance was problematic only during the hot-dry year 1986. In 1986, the base-case load was reduced an equivalent of 3 days at Browns Ferry. Assuming full power operations, Colbert exceeded discharge limits for almost 1 month.

During the hot-dry year 1986, the number of plants impacted and the incidences of thermal violations increased with increasing air and water temperature. As illustrated in Figure 4, tower usage was required at Sequoyah for a 2°F increase in air temperature and became significant (30 days) at T+4. At the extreme (T+8), SQN would be shut down for over 1 month due to its safety limit. Browns Ferry experienced 1 to 3 weeks of additional reduced load for the temperature increments analyzed. Plants on the lower Tennessee and Cumberland rivers (Widows Creek, Colbert, and Cumberland) exceeded thermal limits an additional 1 week to over 1 month for the T+4 and T+8 simulations, respectively.

At all plants analyzed, except Bull Run, thermal limits were not exceeded during the cold-wet and mean years, even when temperatures were increased incrementally.

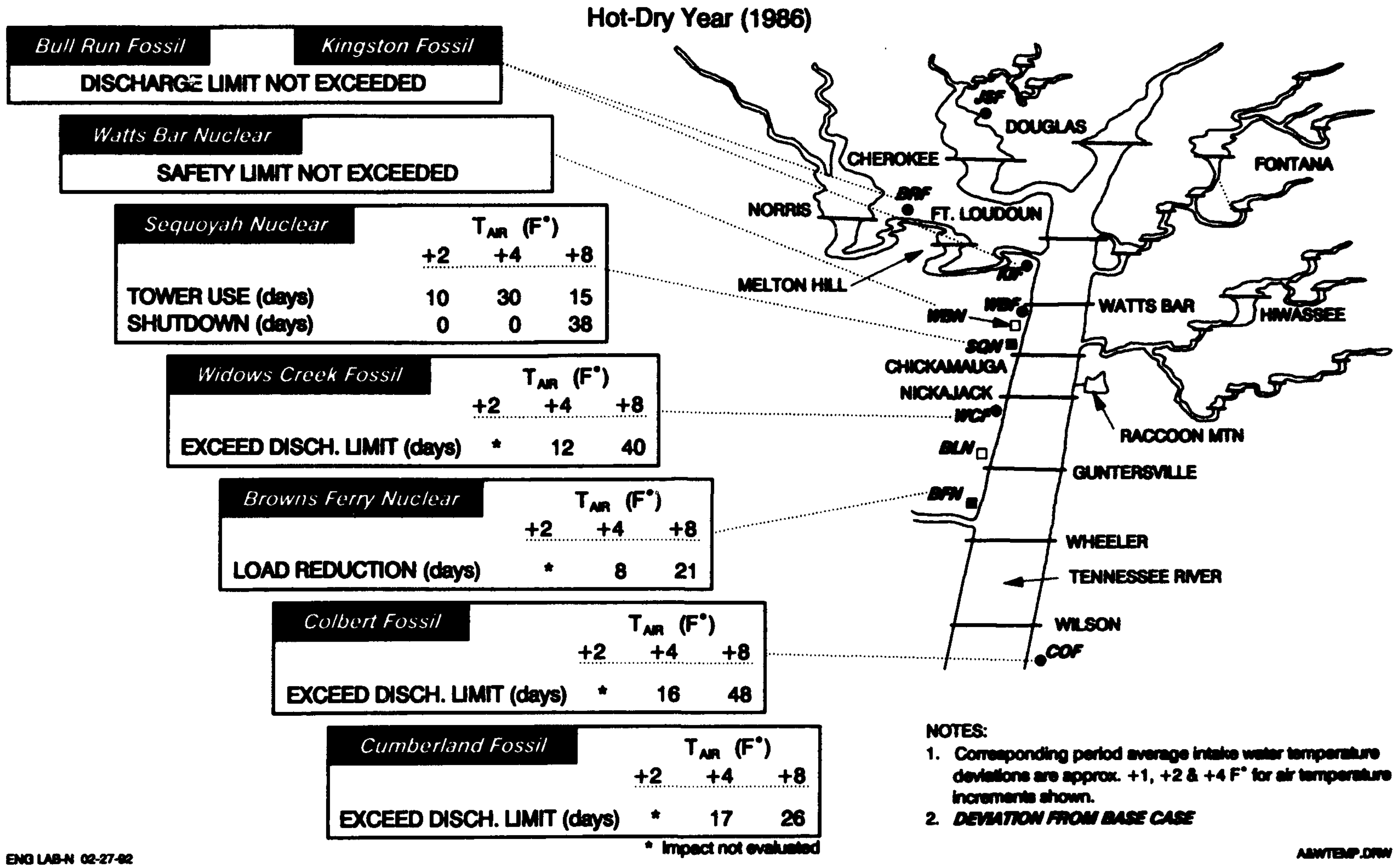

Figure 4. **Impact of increased air and water temperature on environmental and safety compliance at selected thermal power plants.**

RESULTS

The base-case simulations illustrated that some level of the load reduction from maximum generation occurred under current climate conditions. The magnitude of the load reductions varied with the plant type and configuration, plant location, and the type of year. The smallest base-case load reductions (< 2 days) occurred at Bull Run and Kingston Fossil plants, which receive relatively cool water from Norris Dam. The largest load reductions (> 1 month) were experienced by Watts Bar, a closed-cycle nuclear power plant. Base-case load reductions at Sequoyah Nuclear, Browns Ferry Nuclear, and Paradise Fossil plants were relatively moderate, ranging from 4 to 11 days per year. In general, the largest base-case load reductions occurred in the hot-dry year 1986. Base-case load reductions were as much as twice as high in the hot-dry year than in the cold-wet year.

The impact of incremental changes in air and water temperature on plant performance was plant specific, depending on plant design, the stringency of environmental and safety constraints, plant location, and the type of year (see Figure 5). Overall, incremental impacts were more severe at the nuclear plants than the fossil plants evaluated in this study; and the greatest load reductions generally occurred in the hot-dry year.

Bull Run and Kingston Fossil plants appeared the most resilient to increased temperatures. Over the range of temperatures evaluated, incremental load reductions were minimal (less than 0.4 days under worst case conditions). BRF and KIF received relatively cool releases from Norris Dam and operated fairly efficiently in this range of inlet water temperatures.

Incremental impacts at Paradise Fossil, where cooling towers are present, were greater than at BRF and KIF, but less severe than at the other modeled plants. Under worst case conditions (1986, T+8), PAF lost close to 3 additional days of generation.

At Watts Bar, a closed-cycle nuclear plant, annual load reductions under base-case conditions were relatively high. The impact of incremental changes, however, was more moderate and consistent for all types of years. Under the worst case condition (1986, T+8), WBN experienced an additional 13 days of lost load. Forced shutdowns were not required at WBN due to NRC safety limitations; however, intake temperatures were within a few degrees of the 85°F safety limit.

At Sequoyah Nuclear Plant, the incremental impacts of increased temperatures were minimal under normal to cool conditions, but significant in the hot-dry year 1986. At Browns Ferry Nuclear, incremental impacts were apparent during all years; the most dramatic impacts, however, also occurred in 1986. During this hot-dry year, the impacts of increased temperatures appeared to become critical between +4°F and +6°F air temperature.

At +4°F during the hot-dry year, substantial incremental tower usage (> 1 month) was required at SQN and BFN. Although, the safety intake limit was not exceeded at +4°F at either plant, there were 9 days at Sequoyah when intake temperatures were within 0.5°F of the 85.4°F limit. At +6°F, the safety intake limit was exceeded at Sequoyah, resulting in more than 2 weeks of plant shutdown.

Under the worst case conditions (1986, T+8), SQN experienced an additional 40 days of equivalent lost load for the year. Most significant, the majority of these load reductions (38 days) resulted from forced shutdowns. Worst case conditions at BFN resulted in an additional 22 days of lost power and a 47-day increase in tower usage. SQN and BFN experienced the greatest percentage increase in lost load. Sequoyah, due to its safety limit, was particularly sensitive to increased temperatures in the hot-dry year, realizing an almost 500 percent increase in equivalent lost days of load under worst case conditions.

The combined effect of increased air temperature and associated water temperature on plant performance for all six plants for the worst case condition (1986) is summarized in Table 2. In a hot-dry year, under base case conditions, the difference between annual maximum generation and simulated generation was 2,920 gigawatt-hours (GWh), representing a loss of full load from these six plants for 13 days. A 2°F increase in air temperature resulted

Table 1.

Characteristics of Six Representative TVA Thermal Power Plants

PLANT	CATEGORY	COOLING TOWERS		LOCATION [2]	CHARACTERISTICS			ANALYSES ASSUMPTIONS			
		Type	Mode of Operation [1]		No. Units	Rated Capacity (MW/unit)	Total Capacity (MW)	No. Units	Peak Net Capacity (MW)	Maximum Generation [3] (GWh/yr)	Maximum Generation [3] (GWh/day)
Bull Run (BRF)	Fossil (Large)	–	–	CRM 48 Melton Hill Res.	1	950	950	1	884	7,832	21
Kingston (KIF)	Fossil (Small)	–	–	CRM 3 Watts Bar Res.	9	150 (U1-4) 200 (U5-9)	1600	9	1589	13,744	38
Watts Bar [4] (WBN)	Nuclear (PWR) [5]	Natural Draft Counter Flow	Closed	TRM 528 Chickamauga Res.	2	1270	2540	1	1204	10,558	29
Sequoyah [4] (SQN)	Nuclear (PWR) [5]	Natural Draft Cross Flow	Mixed	TRM 484.5 Chickamauga Res.	2	1220	2440	2	2344	20,569	56
Browns Ferry [4] (BFN)	Nuclear (BWR) [5]	Mechanical Cross Flow	Mixed	TRM 294 Wheeler Res.	3	1152	3456	1	1083	9,487	26
Paradise (PAF)	Fossil (Large)	Natural Draft Counter Flow	Mixed (U1-2) Closed (U3)	GRM 100	3	650 (U1-2) 1150 (U3)	2450	3	2342	20,507	56
						Totals	13,436		9,436	82,894	226

NOTES:

1. Mode of Operation:
   - Closed = Recirculating cooling
   - Mixed = Once-through, Once-through with cooling, or Recirculating cooling
2. Location:
   - CRM = Clinch River Mile
   - TRM = Tennessee River Mile
   - GRM = Green River Mile
3. Maximum generation assumes continuous operation at peak capacity
4. Major dates of operation:
   - WBN - Never operated
   - SQN - 11/80 to 8/85; 5/88 to Current
   - BFN - 8/74 to 3/75; 9/76 to 3/85; 7/91 to Current
5. PWR = Pressurized Water Reactor
   BWR = Boiling Water Reactor

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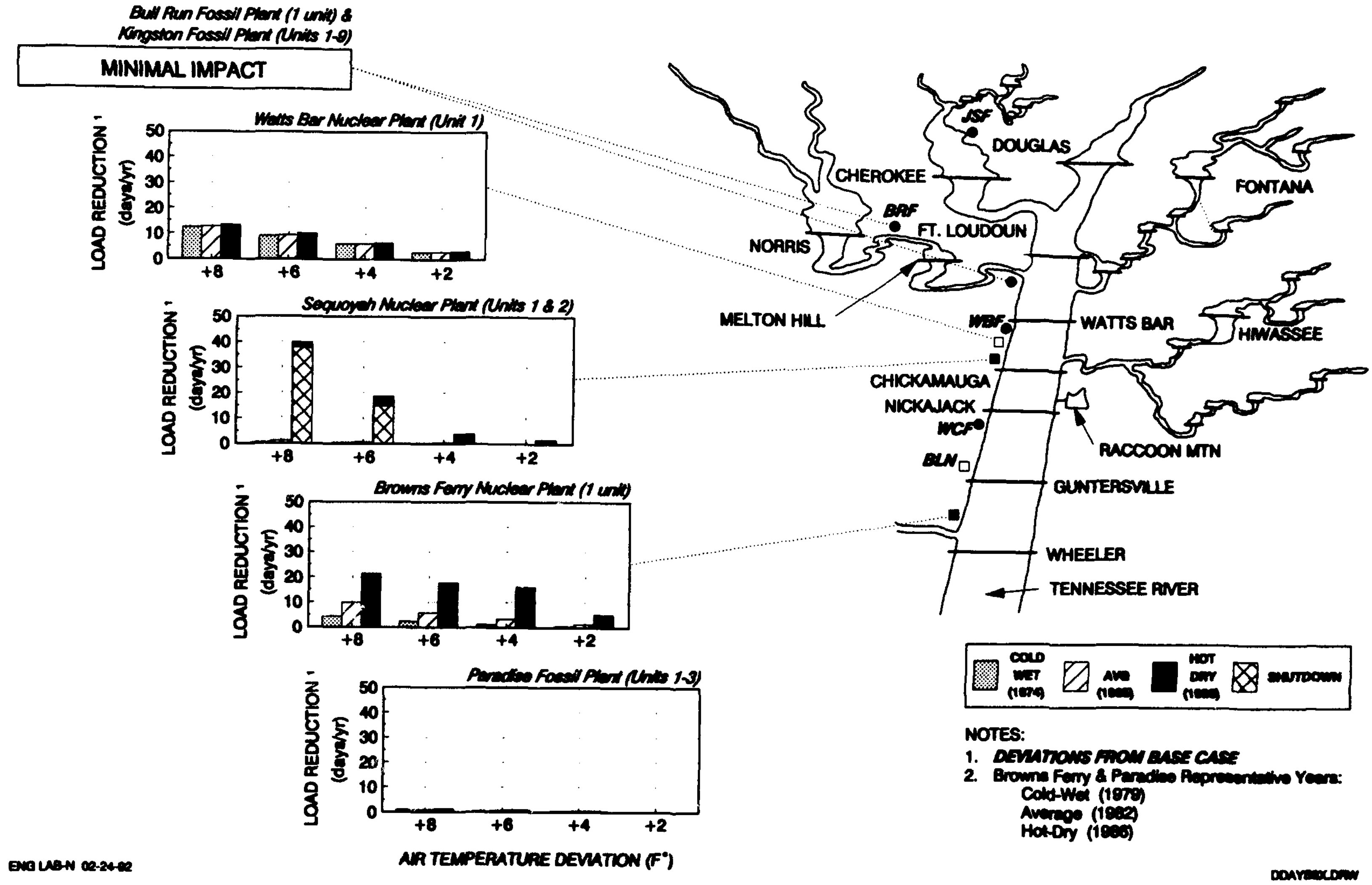

Figure 5. **Impact of changes in air and water temperature on annual plant performance at selected TVA thermal power plants.**

Table 2.

The Combined Impact of Increased Temperature on Plant Performance at Six Thermal Plants for a Hot-Dry Year (1986)

Six Plant Total *(Hot, Dry Year 1986)*

AIR TEMP. (F°)	MAX WATER TEMP. (F°)	LOST GENERATION (GWh/yr)	EQUIVALENT LOST DAYS[1] (full plant days/yr)	% SYSTEM GENERATION[2] (%)
BASE		2,919	13	2
DEVIATION FROM BASE CASE				
+2	+1	357	2	-
+4	+2	881	4	1
+6	+3	1,886	8	1
+8	+4	3,297	15	2

6 plant capacity (BRF, KIF, WBN, SQN, BFN, PAF)............... 9436 MW
6 plant maximum generation... 82,694 GWh/yr

TOTAL SYSTEM CAPACITY[3]................................... 30,748 MW
NET SYSTEM GENERATION[4]................................. 135,700 GWh

NOTES:
1. Based on 6 plant total maximum generation of 226 GWh/day.
2. Lost generation compared to net system generation.
3. 1990 system capacity adjusted to include Watts Bar (1 unit) & Browns Ferry (1 unit).
4. 1990 system generation adjusted to include Watts Bar & Browns Ferry.

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in approximately 2 additional full plant days of equivalent lost load (357 GWh), representing a 15 percent increase over base-case conditions. At T+6, incremental days of lost load increased by as much as 62 percent. Under the most extreme condition (1986, T+8), the six plants lost an additional 3,300 GWh or 15 days of load for the year, representing as much as a 115 percent increase over base-case conditions.

The computed incremental losses in load represent only a small percentage of net system annual generation (less than 2 percent under worst case conditions). During an extremely hot-dry year, however, increased temperatures could still significantly affect the thermal power production system. The timing of load reduction was not evaluated in these sensitivity analyses. However, given the sequential location of these plants on the Clinch and Tennessee rivers, it is likely that most of the load reductions would occur in a similar time frame during the hottest part of the summer. Issues such as system reliability could become important and warrant further investigation.

Assuming that the three nuclear plants considered are operational, these six plants represent more than 30 percent of TVA's total power system capacity. Consequently, it appears that due to environmental constraints and internal plant limitations, small increases in air temperature (more than +2°F uniformly incremental over the year) beyond the historically extreme conditions in 1986 could cause "operational headaches" or inconveniences in meeting system load requirements during periods of peak demand. If hot-dry-year temperature increases were to approach +6°F, the power system could be seriously stressed during critically hot periods due to environmental constraints and NRC safety limits. The TVA power system appears resilient to temperature increases during the cold-wet and mean years.

CONCLUSIONS

A series of models was used to quantify the relationship between changes in air temperature, associated changes in water temperature, and power plant performance. Based on single-variable sensitivity analysis and the assumptions used in the study, the following major conclusions can be made concerning the sensitivity of the TVA reservoir and power supply systems to extreme meteorology.

Water Temperature: The dominant variables that influence the thermal response of dam release and river-system water temperatures are air temperature and solar radiation. For each 1°F increase in air temperature, water temperatures are generally increased by 0.25°F to almost 0.50°F depending on the type of year and location in the reservoir system. Mainstem reservoirs are more sensitive to changes in meteorology than are deep tributary reservoirs.

Environmental Compliance and Safety Limitations: Increased air temperatures and associated water temperatures can cause plant deratings, cooling tower usage, and/or forced shutdowns due to environmental constraints and/or safety water intake limits. Incremental impacts are most severe in a hot-dry year. Vulnerability is plant specific, depending on plant design, the location of the plant, and the stringency of the regulatory constraints.

Power Plant Performance: The dominant environmental variables affecting thermal power plant performance are water temperature and wet-bulb temperature (in the presence of cooling towers). Due to internal plant limitations and environmental constraints, some level of load reduction from maximum generation is apparent under current climate conditions for all types of years, with the largest base-case load reductions generally occurring in the hot-dry year. The effect of incremental changes in air and water temperature on plant performance is plant specific, depending on plant design, the stringency of environmental and safety constraints, plant location, and the type of year. The greatest incremental load reductions generally occur in the hot-dry year. Under hot-dry conditions, increased air temperature impacts appear to become critical between +4°F and +6°F.

Load reductions due to increased temperatures represent a small percentage of annual net system generation. However, during an extreme hot-dry year, temperature-induced load reductions could significantly affect the power supply system and could raise system reliability issues during critically hot periods. Small increases in air temperature (+2°F) beyond historically extreme conditions could cause "operational headaches" in meeting system load requirements during peak demand periods. If hot-dry-year air temperature increases were to approach +6°F, the power system could be seriously stressed due to environmental constraints, NRC safety limits, and internal plant limitations. The TVA power system appears resilient to temperature increases in the wet-cold and mean years.

ACKNOWLEDGMENTS

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CLIMATE CHANGE AND WATER RESOURCES IN TEXAS

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ABSTRACT

Except for the coastal plain in the East, much of Texas is semi-arid. Historically, the state has suffered from periodic droughts as well as flooding. Cities and agriculture are the main water users. The population has doubled since the severe drought of the 1950s, and increased urban demand is predicted through 2040. Irrigated agriculture was at an all-time high during the 1970s. Since then irrigation using groundwater has declined, while irrigation using surface water has increased. In 1990, irrigation used 70 percent of groundwater and more than 40 percent of surface water consumed in the state. Additional stress on water resources is likely to result from climate change. The authors, working with a team of graduate students, analyzed water supply and demand in the Trinity, Colorado, and Rio Grande basins. These basins are located in different climate zones, ranging from wet to dry, and supply water to the major population centers in the state as well as agriculture. The study team constructed water budgets for each of the hydrologic regions, using three supply-and-demand scenarios: (1) demand projected for the year 2000 combined with meteorology during the drought of record, (2) demand projected for 2030 combined with meteorology during the drought of record, and (3) demand projected for 2030 combined with drought of record plus climate change meteorology. For the climate-change scenario we assumed an increase in temperature of 2°C and a 5 percent reduction in precipitation. The model simulations show difficulties in meeting demand in the year 2030 under drought-of-record supply conditions. Shortages will become severe under climate-change conditions. The most serious problems will be encountered in the Rio Grande. Improved water management can alleviate shortages. Management options include conservation, shift to dryland farming, changes in water pricing, and integrated river management of the major river basins.

INTRODUCTION

Texas is a semi-arid state, though there are pronounced regional differences in surface-water supplies. The availability of water is vital to the state's economic stability and for future growth. As one moves from the Gulf Coast to the west, population density drops in rough proportion to the amount of average annual rainfall. Water policy and water management are controversial issues under current conditions. They will be even more important as the state grows. The time frame for water planning spans many decades. The incremental impacts of climate change need to be taken into account now in order to effectively plan for the future.

Gleick (1990) has identified five vulnerabilities of regional water systems: insufficient storage capacity, rising water demand, overdrafting of groundwater, dependence on hydroelectric power, and frequent or intensive floods and droughts. Texas, under current conditions, is vulnerable in three of the five categories: demand, groundwater, and extreme events. Demand is driven primarily by continued population growth. The state's current population of 17 million has doubled since the drought of record in the 1950s. Two large metropolitan areas--San Antonio and El Paso --depend on groundwater as their principal source of water, and irrigated agriculture in the High Plains uses groundwater from the Ogallala aquifer, which is a nonrenewable resource. Texas experiences intense coastal storms that can bring heavy rainfall and flooding to the coast or farther inland. Historically, the state has suffered from three major droughts each century. Often the drought is finally broken by a major storm causing severe flooding. These conditions must be taken into account by water managers irrespective of global warming. As in many other places, however, the lessons of past drought are not easily remembered once the last drought has become history. To this date, the state does not have a drought contingency plan.

Gleick's study is based on a comparison of 21 U.S. water resources regions. Two of these regions are located inside Texas. There vulnerabilities are as follows. The Texas Gulf region is highly vulnerable because of groundwater overdrafting, moderately vulnerable due to variability in streamflows and increase in demand, and somewhat vulnerable due to limited volume of storage capacity. The Rio Grande water resources region has large reservoirs, and seems safe on this score. Yet the region is highly vulnerable due to extreme variability in streamflow and rapidly increasing demand. At present, 64 percent of streamflow is used, which far exceeds the generally accepted safe norm of 20 percent of available streamflow. The region is also moderately vulnerable as a result of groundwater overdrafting.

Scope and Methodology

Aggregating water basins into water resources regions provides a first assessment of potential water supply problems. Yet, this method may hide problems that only study of individual river basins can reveal. Gleick himself makes this point. Our study (Schmandt and Ward, 1991), therefore, examines the vulnerability of three river basins in Texas: the Trinity River in north Texas, the Colorado River in central Texas, and the Rio Grande/Rio Bravo on the border with Mexico. These basins are representative of the wide range of climatological and geographical variability in Texas. Mean precipitation is 711 mm per year, with a range from over 1,397 mm in southeast Texas to less than 254 mm in far west Texas. The three watersheds supply water to several of the state's large population centers--Dallas-Forth Worth, Houston, Austin, El Paso, and the lower Rio Grande Valley.

We ask whether the hydrologic resources in the three water basins will be adequate to meet two climatological contingencies. First, can the basins meet current or future demand if supply is reduced to what it was during the drought of record in the 1950s? Second, how will global warming affect future supply and demand? In a followup study we ask what policy and management options should be considered to make better use of supplies (Schmandt, Ward, and Hadden, forthcoming).

The time frame for our analysis reaches back to the 1950s, when most rivers in Texas experienced drought-of-record conditions, and forward to 2000 and 2030. For the year 2000, we simulate a repeat of drought-of-record conditions combined with projected demand. For the year 2030 we run two simulations. First, we compare projected demand to drought-of-record streamflow. Then we compare projected demand to streamflow under the combined effects of the drought-of-record and global warming. Regional predictions of the effects of climate change are uncertain. The spatial resolution of general circulation models (GCMs) is coarse relative to the spatial requirements for analyzing water resources: most GCMs employ a grid size that results in only one or two data points for the entire state of Texas. Grotch (1988) compared the NCAR, GISS, GFDL, and OSU models for air temperature and precipitation, versus a baseline of historical climatology. He concluded that the models compare favorably for seasonal or annual temperature averages over large areas, but they show substantial disagreements in detailed regional distributions. Moreau (1988) concluded from his interpretation of GCMs that Texas would experience a 4°C increase in temperature. This is higher than the global average increase predicted by the Intergovernmental Panel on Climate Change of 0.3°C per decade (IPCC, 1990). We used a conservative increase of 2°C warming by 2030.

The predictions for changes in precipitation vary widely among the models. GISS, NCAR, and GFDL models display markedly different results for both precipitation and soil moisture, though the Texas area is consistently depicted as a decrement in moisture. However, because the water budget used by GCMs is overly simplified, these results must be used with caution. Kellogg and Zhao (1988) contrast the predictions for five models.

They find a consensus for drier conditions in the southern states and Mexico, with wetter summer conditions on the coastal plain, as indicated by soil moisture. Moreau (1988) finds decreases of precipitation in the Texas area for the spring season. Revelle and Waggoner (1983) calculate that for basins with a weighted average precipitation of 400 mm/year, a 2°C increase in temperature causes a 30 percent decrease in runoff. We based our assumption related to precipitation mostly on reasoning from the predicted change in temperature using historical associations between precipitation and temperature (Webb and Wigley, 1985). This led us to assume a 5 percent decrease in precipitation by the year 2030, which is probably conservative.

Because model predictions at the regional level are imprecise and the time frame for the doubling of CO_2 is uncertain, we attached much importance to using actual meteorological data recorded during the drought of record during the 1950s. This approach, in our view, makes the study results more meaningful for water resources managers who are as yet reluctant to consider global warming as a factor in planning.

Thus, to assess the vulnerability of water resources in the three hydrologic regions, we used the following scenarios:

- *Simulated drought in the year 2000.* Demand based on projected changes, supply based on drought-of-record meteorology.

- *Simulated drought in the year 2030.* Demand based on projected changes, supply based on drought-of-record meteorology.

- *Global warming conditions in the year 2030.* Demand based on projected changes, supply based on drought of record and changed climate conditions. The latter defined by a temperature increase of 2°C and decrease in precipitation of 5 percent.

All three scenarios use population and demand projections developed by the Texas water planning agencies (Texas Department of Water Resources, 1984; Texas Water Development Board, 1989 and 1990). The first scenario is designed to establish a short-term baseline and identify immediate policy concerns. The second scenario provides a forecast of possible water resources conditions in Texas 40 years into the future without reference to climate change. The last scenario applies reasonable regional climate-change effects on water resources in 2030.

The 2030 climate-change scenario focuses on drought, and does not take into account the possibility of increased storms, and resulting precipitation, in the coastal band close to the Gulf of Mexico or farther inland. The climate-change literature frequently mentions this possibility without, however, offering any quantitative predictions. From a water supply perspective, increased storm activity could be important for the Rio Grande region, which is deficient in rainfall. The more northerly portions of the Texas Gulf coast receive much higher rainfall under current conditions. Until better information about storm frequency and altered storm paths is available, quantitative estimates will remain speculative.

The water resources in each basin, and under each scenario, were studied quantitatively by means of water balance budgets. This is a computer-based accounting of sources and losses of water within a basin and includes reservoir capacity for water supply and nonsupply purposes, such as flood control or recreation. The water budget developed for the project differs in two important respects from water budgeting techniques used in water resources planning by state water agencies. First, state agencies use annual data while we used monthly data. This made it possible to identify shorter term periods of water shortages during a given year. Second, the practice in state water budgeting is to start with the measured riverflows as a "given." This study, instead, begins with precipitation and air temperature as the prime controlling factors from which riverflow is calculated. This allows direct computation of the effects of climate change on water supply. Each river basin was subdivided into several zones in order to better depict changing climatological conditions. The water budgets were tested and validated against observed riverflows for each basin to ensure that the water budget had captured the principal hydrologic factors in the basin. The details of water budget methodology are described by Ward (1991). In the remainder of the paper we present a profile of each of the water basins and the results of the water budget analysis. Each profile includes discussion of regional water policy and management issues.

The Trinity River

Overview

The Trinity River is 1,420 km long, originates in the semi-arid northwest of Texas (average annual rainfall 685 mm), and flows into Galveston Bay in the humid coastal part of the state (average annual rainfall 1,295 mm). Compared to other river basins in Texas, the Trinity receives abundant rainfall. The Trinity is an important source of fresh water for the estuary, and provides water for municipal use to the two most populous metropolitan areas in the state--Dallas-Fort Worth and Houston. Until recently, Houston relied mostly on groundwater and surface water from the San Jacinto River. Over-drafting of groundwater has caused subsidence in coastal areas. Houston, therefore, will need to rely more heavily on the Trinity River to supply its growing population. Agriculture, mining, and power generation make up only a small portion of the total water demand in the basin.

In the upper Trinity, the river channel is narrow and surface runoff is rapid. Frequent flash floods result during periods of intense thunderstorms. At other times, streamflow is erratic. Further downstream, the river is susceptible to flooding with prolonged rise and recession stages. The May 1990 flood was the most severe experienced in many parts of the basin. The drought of 1951-1956 was the most severe drought in the last 100 years. Average annual runoff during this time was 142 acre-feet (af) per square mile compared with 310 acre-feet per square mile on average.

Economic Activities

The total population of the basin in 1989 was 3.8 million. The basin population is expected to more than double by 2030. Municipal and recreational water demand is highest in the Dallas-Fort Worth region. Above the metroplex, dryland crops dominate close to the river and rangeland farther inland. Below Dallas-Fort Worth, the Trinity basin is rural. Numerous reservoirs use cooling water for generation of steam electric power. Commercial fishing, including the cultivation of oysters in Galveston Bay near the mouth of the Trinity, represents a major industry that depends on assured streamflow. Galveston Bay provides half of the annual Texas shellfish harvest, and a significant portion of the finfish harvest. Thirteen percent of river water is used for agricultural irrigation, mostly for rice.

Basin Management

Basin management is fragmented. Many agencies are involved. The Trinity River Authority (TRA) and the U.S. Army Corps of Engineers exercise some basin-wide authority. The TRA, however, does not control parts of the upper Trinity nor does it have enforcement powers. The state legislature created TRA primarily as a planning agency. In many parts of the river, the TRA also supplies drinking water and provides waste-water treatment. The TRA owns and operates Lake Livingston, which was built in partnership with the city of Houston and will become a major source of water for the city over the next several decades. Portions of water from Lake Livingston are sold for rice irrigation, for which releases are made for downstream diversion. In addition, TRA must release enough water to control intrusion of salt water. All other reservoirs in the Trinity basin are owned by separate water agencies and cities. While the TRA provides guidance on water planning, drought management, and conservation, it has no formal authority over cities or other water agencies. The Corps of Engineers operates several reservoirs in the upper

Trinity basin, primarily for flood control. As a result of the devastating 1990 flood, the Corps was mandated by Congress to prepare a study on flood control in the entire basin.

Critical Issues

Water quality ranks highest. Population growth continues at a rapid pace, and further increases are predicted. During periods of low streamflow, water quality suffers. At times, the Trinity carries as much as 95 percent effluent from treatment facilities. Many reservoirs suffer from algae growth and degraded quality due to accumulated nutrients aggravated by long detention times. Much of the mainstem of the Trinity is unsuitable for recreational, municipal, or industrial use. If climate change results in less flow, this will reduce the amount of river volume available for diluting the concentrations of pollutants, and further degrade water quality. This can result in increased pressure to further regulate existing dischargers.

As a result of two dry summers, drought contingency plans are finally being prepared for the upper Trinity. Implementation will be difficult in the absence of basin-wide authority. When the city of Houston begins to draw water from Lake Livingston, it will compete for water rights with Dallas-Fort Worth. While there is significant yield at present, reduced runoff from climate change and the absence of an agency empowered to enforce rules for the entire river could result in a long legal and political battle Even so, the problems to be faced in the Trinity basin will be less serious than those likely to be encountered in the Colorado and Rio Grande basins.

Projected Demand and Supply

At present, 72 percent of water in the Trinity basin is used for municipal purposes. Total demand for all uses is 940,016 acre-feet, while total supply amounts to 2.9 million acre-feet (maf) per year. Less than 10 percent of need (0.24 maf) is met from groundwater, and this is not expected to increase in the future. New demand will have to be met from increased use of treated water, construction of new reservoirs, or inter-basin transfers. Water utilities along the river are already making plans for increased use of waste water. This practice will be widely in place by 2030. Most sites for reservoirs have already been developed. In the upper Trinity, where most of the demand is centered, no promising sites remain. In the central and lower basins, 13 new reservoirs are planned. They will have a combined capacity of 0.7 maf. The largest project, Tennessee Colony, is currently on hold because of conflicts over lignite reserves in the area that would be flooded. Inter-basin transfers are planned from the Red, Sabine, and Sulphur rivers. They will be expensive and controversial.

Demand will increase rapidly. Population by the year 2000 will reach 4.6 million. Under a rapid growth scenario, it may reach 7.6 million by 2030. Table 1 shows projected water demand using high and low population growth scenarios. The Texas Water Development Board, in its most recent water plan (1990), also projected high and low water use practices. High demand assumes continuation of current water practices, while low demand requires improved conservation methods. In the worst case--high population growth and no conservation--demand will reach 2.1 maf by 2030. Low population growth combined with conservation would reduce demand to 1.6 maf. TRA estimates that when all planned reservoirs are completed, the basin will have 3.34 maf of surface water available.

Water Budget Results

In the Trinity basin, the drought of record lasted from 1951 to 1957. Municipal reservoirs were separated from power reservoirs because most water used for cooling is reused in the same reservoir. For this reason, declines in municipal supplies are more pronounced. However, water supply for power generation under climate-change conditions will also be stressed as a result of the combined effects of increases in population, air-conditioning

TABLE 1
Trinity River -- Projected Water Demand
(Acre-Feet Per Year)

Sector	1990	2030 High	2030 Low
Municipal	675,472		
no conservation		1,568,927	1,408,093
with conservation		1,334,833	1,198,129
Manufacturing	97,664	241,103	170,542
Steam Electric	47,418	145,300	102,500
Irrigation	79,866	99,279	76,904
Mining	17,202	46,885	46,885
Livestock	22,394	30,296	30,296
Total	940,016		
no conservation		2,131,790	1,835,220
with conservation		1,897,696	1,625,256

Source: Texas Water Development Board, 1990

load, and forced and natural surface evaporation. We aggregated into two the three Trinity zones used in state planning; one for the upper and one for the middle/lower Trinity. The upper Trinity, including the Dallas-Fort Worth metroplex, shows significant changes; the lower Trinity, because of lower population and demand, does not. The findings for municipal reservoirs in the upper Trinity are summarized in Table 2. Applying the meteorological conditions of the drought of record to year 2000 population and water demand shows that municipal reservoir supplies will decline rapidly, reaching their lowest level in the sixth year of drought. The downward trend will be more severe in 2030. If monthly, rather than annual, streamflows are considered, shortages will be even more pronounced, with reservoir capacity falling to as little as 43 percent during the most stressed months. Reservoir levels under scenario 2030C (with climate change) will be perilously low, reaching 20 percent of capacity by year seven of the drought, and 13 percent by the ninth year. On a monthly basis, reservoir levels during the most stressed months (October through March) will fall as low as 6 percent in year nine of the drought. Such levels would be unacceptably low.

TABLE 2
Upper Trinity River
Municipal Reservoir Volume
(Percent of Conservation Capacity)

Year	1	2	3	4	5	6	7	8	9	10
2000	98	94	92	88	80	69	79	94	92	100
2030	97	91	83	77	68	58	60	82	78	78
2030C	95	81	71	58	41	22	20	28	13	18

Possible Effects on the River Basin

Water budget results show the upper Trinity to be highly vulnerable to the effects of a prolonged drought similar to the drought experienced during the 1950s. Municipal reservoirs would be rapidly depleted and would be slow to recover. A changed climate would result in severe supply limitations. Under these conditions municipal supplies could be exhausted after a few years of drought. A number of mitigating circumstances were not taken into account in the analysis. New reservoirs can be built on the lower Trinity. However, this part of the river is less at risk in the first place. Inter-basin transfers could bring relief to the upper Trinity, but the financial and political feasibility of inter-basin transfers is unknown.

The issue of highest concern is the management structure of the Trinity. The fragmented administrative system that now exists is ill prepared to cope with major droughts or climate-change-induced supply limitations. In principle, the basin can be operated as a single system during a drought. But coordination and enforcement will be difficult. The appointment of a water master may help. A water master is already in place for the Rio Grande, and one may soon be appointed for the Colorado. The Texas Water Commission has plans to use the water master program throughout the state but implementation may be delayed due to more urgent priorities. Trinity River water agencies also need to educate the public on the concept of reuse of waste water and invest in research to improve its technical feasibility.

The Colorado River

Overview

The Colorado River basin extends about 1,000 km from the southeast portion of New Mexico, across Texas to the Gulf of Mexico near Matagorda Bay. The upper portion of the river is located in the High Plains, where the terrain is flat and the climate semi-arid. Average precipitation increases as the river travels east across Texas. Mean annual precipitation ranges from 381 mm in the northwest to about 787 mm at Austin and 1,092 mm at the coast. Average annual runoff ranges from less than 50 acre-feet per square mile in the upper portion of the river to 350 acre-feet per square mile near the mouth of the Colorado River. Runoff is the principal contributing source for the river. Severe flooding also occurs. Some of the highest rainfall rates in the United States have been recorded in the river basin. The drought of record occurred during the 1950s.

Ninety percent of the river's drainage area is impounded. The principal impoundments are the Highland Lakes chain of six reservoirs in central Texas, operated by the Lower Colorado River Authority (LCRA), with a combined capacity of 3.1 maf. In addition, the basin has another nine major reservoirs totaling 1.5 maf, and several smaller limited-purpose reservoirs.

Economic Activities

Population in the basin, now 1.4 million, has doubled since 1950, and is likely to double again by 2030. Under a high population projection, it will reach 2.7 million by 2030; under a low projection 2.3 million. The population is concentrated in the upper (41 percent) and middle (47 percent) parts of the river; only 11 percent live in the lower part of the river. A major shift in population from rural to urban areas is under way. Besides Austin, several other Texas municipalities use surface water in the Colorado River basin, including Odessa, Midland, San Angelo, and Big Spring.

The economy in the upper and lower Colorado basin depends heavily on irrigated agriculture. In the north, oats, wheat, and cotton are grown. A large portion of the wheat crop is irrigated. In 1985, the northern zone irrigated 792,000 acres. In the south, rice is the major cash crop; 220,000 acres are irrigated. Because rice requires much more water per acre than other crops, the demand on the Colorado is heavy. In the middle zone of the river, urban use is dominant and rapidly growing.

Basin Management

The three primary water managers for the Colorado River are the Upper Colorado River Authority, the Colorado River Municipal Water District, and the Lower Colorado River Authority (LCRA). The latter is by far the most important agency, responsible for flood control, water supply, and water quality from Lake Buchanan--the first in the Highland Lakes chain--to the Gulf. The agency is also a wholesale supplier of electricity to a 41-county area and derives the major part of its revenue from this source. Sale of water to downstream users is another source of income. In recent years, LCRA has become active in environmental protection and has taken the lead in a number of forward-looking initiatives. At present, the agency is developing an integrated management plan for the river. Water quality concerns are high on the agenda.

Critical Issues

Upstream interests, represented by the river authorities responsible for the upper and middle Colorado, have fought vigorously to build Stacy Reservoir. The project is now completed. The LCRA opposed the project, arguing that there was insufficient water in the Colorado River to meet all of the outstanding water rights appropriations. The conflict between upstream and downstream interests is likely to resurface in the future.

Throughout the basin, water supply and flood control goals are often in conflict. A major problem for the future is competition for limited water supplies between urban, agricultural, and recreational users. Balancing flood control and supply goals is difficult, because serious flooding can occur, sometimes at the end of a prolonged drought. In 1952, for example, Lake Travis rose 56 feet in 18 hours and serious flooding would have occurred if the lake had not been depleted by drought conditions. Increasingly, there are also conflicts between municipal and agricultural interests. Rice farmers have longstanding senior water rights; roughly 38 percent of all Texas rice is grown in the coastal reach of the Colorado. Rice farmers claim 73 percent of river water and 80 percent of the LCRA's annual water diversion is for rice irrigation. In 1931, the state legislature passed the Wagstaff Act, which gives highest priority to municipal water use during times of supply shortages. The Texas Water Commission holds that rice irrigators holding water rights predating the Wagstaff Act are exempted from emergency curtailments. Yet the LCRA, in its recently published *Drought Management Plan for the Lower Colorado River* (1990) treats irrigation as an "interruptible" water use, which will be served after priority needs for cities, industry, and instream flows are met.

This policy would force irrigators to take percentage cuts in their water supply during times of shortages, and could eliminate second-crop production in dry years (Jensen, 1991). The issue has not yet been tested in the courts.

Recreation has become an important industry in the Highland Lakes area. Recreational interests desire stable lake levels, which makes it more difficult for the LCRA to order preventive drawdowns. By far the major conflict, however, centers around rapidly growing urban demand. So far, cities downstream from Austin rely on groundwater and hold no surface-water rights. By 2000, the LCRA predicts groundwater shortages for cities in central Texas.

Projected Demand and Supply

There are 26 major reservoirs in the Colorado River basin with a total capacity of 4.2 maf. Current water usage in the upper Colorado amounts to 0.8 maf, in the middle Colorado 0.2 maf, and in the lower Colorado 0.7 maf, for a basin total of 1.7 maf. Irrigation is the largest user category, followed by municipal use. With no additional sources of supply, the Texas Department of Water Resources (1984) estimated that the Colorado would experience a water shortage by the year 2000 and that irrigation would have to be curtailed. More recent estimates (Texas Water Development Board, 1990) predict a decline in irrigation usage. The Stacy Reservoir also adds resources. The general manager of the Colorado River Municipal Water District estimates that the middle Colorado will have adequate water supplies past the year 2030.

Projected water demand for the years 2000 and 2030 is summarized in Table 3. The projections are taken from the 1990 *Water for Texas* report by the Texas Water Development Board. They are significantly lower than predictions made in 1984 (Texas Department of Water Resources). The new projections predict major shifts in water use patterns and an overall reduction in future demand. Significant increases are projected for municipal demand. At the same time, a dramatic decline is projected for irrigation. In the upper Colorado alone, irrigation would drop by more than 50 percent by the year 2030. The new projections are based on a decline of irrigated acreage in Texas during the 1980s after an all-time high had been reached in the 1970s. As a result of urban competition, improved efficiency of water use, and higher costs of irrigated agriculture, the total amount of water used for irrigation and the number of irrigated acres dropped significantly in the 1980s. This trend is likely to continue, affecting water use in the Colorado basin both in the north and the south. In the upper Colorado, irrigation use is projected to decline from 580,768 acre-feet per year in 1990 to 493,814 acre-feet by the year 2030. In the coastal region, dominated by rice production, the decline will be even steeper. In 1990, 622,142 acre-feet were used. For the year 2030, 356,569 acre-feet are projected. At present, rice production accounts for 84 percent of all water use in the coastal region served by the LCRA. LCRA projections for water demand in the basin are higher than TWDB figures, but show the same trend. The agency projects that the amount of water used for rice growing could decline from 870,000 acre-feet per year to under 600,000 acre-feet by the year 2020 (Jensen, 1991).

Water Budget Findings

Even using the reduced-demand projections discussed above, water supply problems will arise in the basin. The most severe shortages were found for the upper Colorado. Table 4 shows the results. Beginning with year 6 of the drought, municipal and agricultural demand cannot be met in 2030 under a changed climate. And even without climate change, shortages will occur in year 8 of the drought. The changed climate leads to empty reservoirs in the simulation or, in the real world, large demand curtailments.

For the lower Colorado (from Lake Buchanan to the Gulf of Mexico) results are less dramatic. In this case, however, TWDB and LCRA estimates of supply and demand in 2000 and 2030 (or 2020, up to which time LCRA has made its projections) differ markedly. Using TWDB projections of rapidly decreasing irrigation demand,

TABLE 3
Colorado River -- Projected Water Demand
(Acre-Feet Per Year)

Sector	1990	2000	2030
Municipal	258,001	310,728	487,318
Manufacturing	31,517	47,742	119,126
Steam Electric	56,100	80,980	99,300
Irrigation	1,221,208	1,099,368	868,781
Mining	55,760	47,210	39,104
Livestock	29,825	34,089	34,089
Total	1,652,411	1,620,117	1,647,718

Source: Texas Water Development Board, 1990

TABLE 4
Upper Colorado River
Annual Municipal Reservoir Level
(Percent of Capacity)

Year	1	2	3	4	5	6	7	8	9	10
2000	97	80	72	62	50	38	24	20	17	18
2030	96	77	65	56	38	20	7	-1	-10	-11
2030C	95	72	57	49	29	-2	-20	-34	-42	-52

the river would be in better shape in 2030 than in 2000. Using higher LCRA projections for irrigation demand, the supply situation turns critical in the sixth year of drought, dropping to 30 percent of reservoir capacity in October of that year. All demands may be met. However, a level of 30 percent of capacity is critically low for planning and management purposes. The 2030C scenario (drought under climate-change conditions) shows moderate problems using TWDB estimates with reservoir volume capacity declining to 59 percent in the sixth year of drought. Using LCRA estimates, the drop would be much more serious and would reach 28 percent. The lowest monthly average would decline to 14 percent of total capacity. It is conceivable that at this point one or more of the reservoirs would be virtually unusable.

Possible Effects on the River Basin

The results of the water budget simulation call for timely action in order to reduce conflict and attempt solutions that minimize economic and social disruption. Many of the issues that need to be addressed already figure in today's political agenda but will become more urgent as a result of global warming. Foremost among these are tensions between recreational, urban, and agricultural users. The long-term economic viability of the rice industry, now using 80 percent of the water taken from the river, will be questioned with increasing intensity. The problems created by a reduction in water supply are compounded by an uncertain long-term international market for Texas rice and a tenuous federal price-support system. Severe economic hardships in the agricultural sector will result from water deficiencies and have a direct effect on the economy of the entire basin. Insufficient supply of water may limit population growth and economic expansion. In regard to water management, the efficiency of multiple jurisdictions needs to be examined. The LCRA has recently withdrawn its opposition to appointment of a water master overseeing the entire basin. An economic analysis of current water rates is needed. At present, water rates in Texas are significantly lower than those in other states. While these low rates have benefits for agricultural and urban users, they may also serve to distort the real value of water and foster a wasteful approach to its use.

Rio Grande

Overview

The Rio Grande originates in southern Colorado, crosses New Mexico, and enters Texas at an elevation of 1,158 meters. The river then flows southeast for more than 1,900 km to the Gulf of Mexico, forming the international boundary between the United States and Mexico from El Paso/Juarez to Brownsville/Matamoros. The total basin drainage area is 471,937 km^2, most of it located in Mexico. Precipitation ranges from 254 mm per year in the western part of the basin up to 610 mm per year along the Gulf of Mexico in the tropical climate of the Rio Grande Valley. The entire river basin, therefore, is arid to semi-arid. The coast is humid, but rainfall is scarce. Occasionally, tropical storms move in from the Gulf, causing short periods of heavy rain and flooding. Evaporation exceeds precipitation throughout the basin, with historical evaporation deficits ranging from a low of 1981 mm per year to a high of 2,819 mm per year.

Early in the century, many large reservoirs were built in New Mexico, causing the flow at El Paso to decrease 96 percent. Below El Paso, streamflow often approaches zero. Farther downstream, waters from tributaries, in particular the Rio Concho in Mexico, are the principal source of water for two large reservoirs that provide surface water to the lower Rio Grande Valley. Falcon Reservoir was completed in 1953; Amistad Reservoir in 1968. In this part of the Rio Grande, only about 4 percent of precipitation falling in the watershed reaches the main river because of high temperatures and parched soils. Flooding and droughts in the lower Rio Grande Valley have resulted in the construction of several dams, including the Anzalduas Diversion Dam, and over 160 km of levees.

There are two large population centers along the Texas-Mexico border. El Paso/Juarez depend almost entirely on groundwater, while the lower Rio Grande Valley uses almost exclusively surface water, due to the poor quality of groundwater in this region. The lower Rio Grande Valley is no valley at all but a delta. It has good soils but requires irrigation to take advantage of them. The valley is known for its abundant wildlife and as a migratory corridor for birds. Assuring adequate streamflow is important for wildlife as well as for discharges into the estuary.

Economic Activities

Nearly 2.7 million people live along the Rio Grande/Rio Bravo from El Paso to the Gulf. People have settled in twin cities on the two sides of the border with intensive traffic between them: El Paso/Juarez near the New Mexico state line, Laredo/Nuevo Laredo in the middle portion of the river, and Hidalgo/Reynosa and Brownsville/Matamoros in the lower Rio Grande Valley. On the U.S. side of the border, population in 1990 reached 1.3 million, and population growth through immigration and natural increase is occurring faster than in any other part of Texas. The U.S. population in the El Paso-to-Brownsville region is projected to reach 2.4 million by 2030. At present, El Paso is by far the largest city, followed by Laredo, Del Rio, Eagle Pass, Pecos, and Brownsville. The 13 Texas counties along the Rio Grande include some of the poorest counties in the nation (4 of the poorest 10). The region suffers from high morbidity and mortality from preventable diseases, low life expectancy, median-incomes near the poverty level, low education achievement, many female heads of household, and high population mobility (Chan et al., 1988). The four counties in the lower Rio Grande Valley have the highest population growth rate in the United States, currently with a population of over 700,000 people, a 23 percent increase over 1980 levels. The area is economically depressed, with high unemployment and some 160,00 people living in so-called colonials without sewage disposal and often without running water in the homes.

The economy is dominated by irrigated agriculture, virtually all irrigated. Ninety-two percent of water taken from the Rio Grande is used for irrigation. The valley is home to one of the most important sources of vegetables and citrus crops in the United States. Other crops are grain, sorghum, cotton, and sugar cane. Irrigation is dependent on adequate water flow in the Rio Grande. So far, irrigators are not concerned about water shortages, but complain about increasing levels of salinity. Other industries include tourism (winter inland, summer on the coast), food processing, shrimp fishing, and wholesaling and trucking for the maquiladoras industry across the river in Mexico. Maquiladoras are assembly plants located in Mexico close to the border that take advantage of low Mexican labor costs and border-zone free-trade arrangements between the two countries. They have grown rapidly over the last 20 years and represent a major part of the economy in the region.

Basin Management

The Rio Grande from El Paso to the Gulf is administered jointly by Mexico and the United States. The International Boundary and Water Commission, under a 1944 treaty between the two countries, manages the river and operates the two most important reservoirs--Amistad and Falcon. The commission allocates water to Mexico and the United States according to the treaty provisions. At the time the treaty was concluded, the United States was given rights to 56 percent of Rio Grande water. This favorable treatment may make it difficult, from a U.S. perspective, to reopen negotiations on other aspects of river management that were not addressed in the treaty, such as water quality and groundwater use. The IBWC is directed by engineers and enjoys a reputation for good technical work, but has operated over the years with minimal local participation and with little concern for environmental matters.

The Texas Water Commission (TWC) administers water rights on the U.S. side of the border through its water master program. The first water master was appointed by the courts in 1971 to prorate, distribute, and allocate Rio Grande water. The position has since been taken over by the state. The water master is the sole agent of the state who has the right to request of the IBWC releases of water from the U.S. share of storage in the Amistad and Falcon reservoirs. The water master operation is funded by user fees. The operating guidelines of the office are based on a detailed budgeting of water rights accounting for municipal, industrial, and agricultural users, and include preservation of predetermined drought-protection levels in the two major reservoirs. Fees charged cover only the administrative and delivery costs for water, and do not reflect a charge for the water itself.

Critical Issues

Population growth and development have resulted in increased water demands and deteriorated water quality. Groundwater in the lower Rio Grande Valley has high salinity levels. At times, salinity is also a problems with surface water. Inadequate or nonexistent water treatment facilities compound the problem of water quality. The city of Nuevo Laredo, for example, will get its first treatment facility, built by the International Commission as a joint project of Mexico, the United States, and Texas, by the mid-1990s.

The IBWC is being sued by the Sierra Club Legal Defense Fund for "systematically destroying critical wildlife habitat along the river without complying with national environmental laws." The IBWC takes the position that it is not subject to the Endangered Species Act. In the El Paso region, groundwater resources are being depleted at a rapid rate. The city of El Paso sought additional groundwater supplies in New Mexico. The suit, which was won by El Paso, caused concern among citizens in Juarez, the Mexican sister city across the river, who fear the depletion of another aquifer on which they depend for water supply. The city of Brownsville wants to construct a dam downstream from the city. The project is controversial because of its impact on streamflow and release into the estuary. The beneficial yield from the new reservoir is estimated to be fairly low.

A number of nongovernmental environmental organizations have offered anecdotal information indicating that border industries are illegally discharging toxic and hazardous chemicals into surface and groundwater supplies in violation of Mexican and U.S. pollution standards. State and federal officials acknowledge that little industrial waste is returning to the United States for disposal from the border maquiladoras, as required by Mexican law. Only 11 notifications of returning waste were filed with the Texas Water Commission for the 400 maquiladoras operating on the Texas border in 1987. In 1990, SEDUE (the Mexican environmental agency) estimated that 52 percent of its maquiladoras generate hazardous by-products. Of these plants, only 30 percent have complied with regulations to provide information on their waste, and only 19 percent are returning their waste to the country of origin or recycling it in compliance with Mexican regulations. SEDUE has confirmed evidence of industrial pollution by recently closing border-area factories, primarily for violations of hazardous-waste laws. One closure involved discharges from a key General Motors plant near Matamoros.

In the lower Rio Grande Valley, groundwater quality is so poor that in most places it is unusable for either agricultural or municipal use. Brownsville and Cameron County withdraw only 1 percent of their water from the Gulf Coast aquifer because the level of dissolved solids is too high. While natural causes are mostly to blame, poor irrigation practices contribute to the poor quality of groundwater.

Some irrigation districts are conserving water by reducing seepage losses. They then sell or lease unused water rights to municipalities. Because the number of water rights exceeds the firm yield of the river, municipalities receive 1 acre-foot for each 2 that they buy, and their priority of use is increased in order to guarantee their supply. It is possible, therefore, that a combination of market incentives (agricultural users can sell water rights separate from their land) and priority allocation to cities can meet much of the increased urban demand. However, agricultural production will decline. The proposed free-trade agreement with Mexico is also likely to shift some agricultural production across the border into Mexico, where labor costs are lower.

Projected Demand and Supply

Our analysis only considers demand and supply from the New Mexico state border to the Gulf of Mexico. This seems reasonable because streamflow below El Paso, as mentioned, is minimal or nonexistent due to upstream impoundments. Of the two main reservoirs Amistad has a storage capacity of 5.66 maf, of which 3.0 maf are assigned for conservation and 2.11 maf are allocated to flood control. Falcon has a total capacity of 3.98 maf, of which 2.67 maf are for conservation and 1.3 maf are for flood control. Without these reservoirs, the riverflow would be extremely variable and would diminish to nearly zero at times during most years.

All of the water of the Rio Grande is currently over-appropriated to its users. The lower Rio Grande Valley recently went through a 3-year drought. In August 1991 irrigation deliveries were temporarily stopped. The situation was reversed shortly thereafter when abundant runoff from Mexican tributaries filled the reservoirs. Irrigation district officers in the valley estimate that the firm yield from Amistad and Falcon can delay reductions for agricultural use until the third year of drought.

Total use of Rio Grande water in 1990 exceeded 2 maf. About 78 percent is used for agriculture. New estimates by the Texas Water Development Board (1990) predict that irrigation usage from surface water will decline slightly, from about 1,063,281 acre-feet in the year 2000 to 1,034,072 in the year 2000. Meanwhile, consumption by municipalities will rise from 158,500 acre-feet to 201,003 acre-feet, and manufacturing use will also rise from 5,644 acre-feet to 7,916. Table 5 shows projected water use by category. There will be a large increase in demand for municipal use, and irrigation is expected to decline slightly. Because of this, overall demand by 2030 will be less than estimated in 1984, when the previous state water plan was published. At that time, a large increase in demand for irrigation was assumed. To meet demand, additional reservoirs or imports from other basins were proposed. These assumptions and recommendations have been radically changed in the 1990 plan.

Water Budget Findings

As for the other basins included in this study, estimates for population growth and changes in demand are taken from TWDB projections. So far, we have not found similar projections for Mexico. Obtaining reliable estimates from Mexico is difficult; thus, demand projections only cover the Texas side of the river. Water supply was estimated from Mexico as well as Texas runoff, and the Texas portion was calculated using the provisions of the 1944 treaty. The results are summarized in Table 6.

Under drought-of-record conditions in the year 2000, the two major reservoirs--Amistad and Falcon--would have a capacity of 39 percent, or 2,366,353 acre-feet by the fifth year, dropping to -4 percent by the seventh year. By the end of the drought of record, the water level in the two reservoirs would rise to 16 percent of capacity. For the year 2030 (without climate change), negative reservoir capacities will be reached in year 6. Capacity levels during the most stressed biennium would lead to even more serious seasonal reductions. The lowest negative volume would occur in October of the seventh year of the drought, when the reservoir volume drops to 1,250,622 acre-feet below empty, or -20.7 percent. For the year 2030, climate-change negative volumes are reached in year 6, and maintained for the entire decade, ranging from an absolute low of -39 percent in year 7 to -36 percent in year 10. During the most stressed biennium, reservoir capacities would fall even more, reaching -50 percent in October of year 7 and -46 percent in July of year 8.

Negative volume capacity, obviously, is a mathematical artifact, based on the assumption that normal seasonal demand is met. It measures the gap between supply and demand. Under real-world conditions, negative volume is impossible. Instead, curtailments would be imposed, either by nature or by society. Thus, the result of the water budget simulations for the two 2030 scenarios offers a strong message: The likely reduction in dependable streamflow in the Rio Grande under conditions similar to the drought of record, and even moreso under climate-change conditions, would seriously threaten irrigated agriculture, industrial development, and drinking-water supplies. The predicted decreases in irrigation use and improvements in conservation fall short of the possible shortages resulting from development and climate change.

Possible Effects on the River Basin

The international nature of the Rio Grande/Rio Bravo makes it mandatory to consider water supply and demand on both sides of the border. At present, the lack of clarity and knowledge about accounting and management procedures in Mexico makes this difficult. State, local, national, and international authorities have fragmented jurisdictions and differing management agendas often driven by conflicting policy and planning interests. The scope and degree of poverty, especially in Mexico, make it far more difficult to allocate resources for water conservation and water treatment. Poverty forces needy communities to favor economic development, even though the environment and natural resources may be further degraded.

TABLE 5
Rio Grande Below El Paso -- Projected Water Demand
(Acre-Feet Per Year)

Sector	1990	2000	2030
Municipal	394,950	500,893	916,042
Manufacturing	19,127	23,716	40,433
Steam Electric	18,600	21,500	28,500
Irrigation	1,712,229	1,672,151	1,583,134
Mining	47,836	55,163	69,358
Livestock	24,667	28,370	22,578
Total	2,217,409	2,301,793	2,660,045

Source: Texas Water Development Board, 1990

TABLE 6
Rio Grande From El Paso to Gulf of Mexico
Annual Municipal Reservoir Level
(Percent of Capacity)

Year	1	2	3	4	5	6	7	8	9	10
2000	94	77	60	50	39	19	-4	4	20	16
2030	92	75	57	48	34	12	-11	-4	10	6
2030C	90	69	47	33	14	-10	-39	-37	-24	-36

In Texas, far more attention has been focused on water quantity than water quality. The existing water supply system will be unable to meet all demands during a prolonged drought. The Wagstaff Act has never been used to allocate water according to user priorities rather than existing water rights. In the Rio Grande, where the Wagstaff Act does not apply due to the international nature of the river, the water master can enforce priorities among Texas users. While this authority has been used briefly in 1991, the program has not been tested yet under extreme drought conditions. Many river authorities, as well as the water master, do not have authority to regulate the quality of the water they deliver. Irrigators are concerned about salinity but this concern does not extend to conventional and toxic pollution.

Water conservation will progress only if a more realistic fee structure for water use is adopted. New dams and reservoirs in the water basin will not bring much relief, and may cause controversy. Conflicts between municipal and agricultural water users are likely to increase. Several municipalities have recently sued for legal rights to agricultural water. This may complicate the market-driven process of diverting agricultural water rights to urban use.

CONCLUSIONS

In a semi-arid state like Texas, enlightened water policy determines the future of the state. Consideration of future water supply and demand is the single most important component of water policy in the state. The study of the Trinity, Colorado, and Rio Grande rivers shows that global warming will affect current water issues and exacerbate conflicts. However, the problems to be encountered are not fundamentally different from those that will occur as a result of population growth and development. Action must simply be taken earlier. The future, without and with global warming, calls for a much more comprehensive, proactive, and basin-wide approach to water resources management than exists today.

The Texas Water Development Board, the state's water planning agency, estimates that 14 major reservoirs will need to be built to meet future demand over the next 50 years. In addition, 29 water conveyance projects will be required to carry water from new and existing reservoirs to areas of greatest demand (TWDB, 1990, p. 1). These estimates assume water savings of 20 percent through conservation efforts (which may be overly optimistic) and do not take the effects of climate change into account. The magnitude and number of these projected structures raise serious concerns about the feasibility of this approach. Other policy options need to receive at least equal attention, such as conservation, pricing of water, and an extension of the water master program. Water supply and water quality need to be considered together, as should surface and groundwater.

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SUMMARY OF REGIONAL SENSITIVITY TO CLIMATE CHANGE IN THE NORTHEAST

John E. Schefter, Chairperson
Michael Krouse, Rapporteur

ABSTRACT

The session centered around four presentations and discussions concerning methodologies for estimating the sensitivities of major northeastern water supplies to potential climate change, descriptions of the possible sensitivities and impacts on supplies and demands, and policy and management responses.

Methodologies

Fiering suggests the use of perturbation analysis with queuing models as an efficient method to estimate the impacts of climate change. Using the Colebrook Reservoir in the Farmington, Connecticut, watershed as a case study, he found the method to be more computationally efficient than traditional simulation techniques and that it produced results very comparable to the simulation approach. He found this method to be well suited for dealing with sensitivities associated with gradual changes in climate and for capturing seasonal effects on a regional scale.

Kirshen's discussion concerned the impacts of climate change on the Boston metropolitan area water supplies. In a case study of the Ware River basin, he applied a rainfall-runoff model that allows consideration of climate-induced changes in temperature and precipitation to estimate impacts on snowmelt, soil moisture, and runoff. Using these results as input to a safe yield model, he was able to derive estimates of system reliability under changed low-flow conditions.

Major provided a planning perspective for dealing with potential impacts of climate change on New York City water supplies. He outlined a set of planning guidelines to be used in considering potential climate-change impacts. They included the following: Water resources planning expertise should be enhanced and planning efforts undertaken over the long run, multi-objective planning should be part of the decision process, and planning should reflect knowledge of the physical impacts of climate change and consideration of human adaptation to environmental change.

Wolock discussed the effects of climate change on the Delaware River basin. Using a basin water balance model and reservoir operations, model climate-change variables, temperature and precipitation were varied to generate effects on basin supply and demand. Also, the analysis considered the effects of increasing carbon dioxide on the stomatal resistance of plants and the consequences for irrigation demand.

Sensitivities and Management Options

The Farmington River-Colebrook Reservoir case considered tradeoffs between flood control storage and water supply under conditions of climate change and demand growth. Fiering found that increases in water supply storage could be made that would meet target demands without a significant increase in the flood risk. However, the effects of climate change on the frequency of hurricanes is not known but is quite relevant to decisions about storage allocation in northeastern flood control reservoirs. Thus, Fiering recommends that a staged transfer of flood storage be undertaken and that flexibility be retained to accommodate climate change and possible increases in hurricane frequencies.

Kirshen's study of the Ware River basin showed that likely impacts of climate change would be that low flows come earlier in the year, last longer, and are smaller. This has dramatic impact on safe yield of the system along with low-flow requirements for environmental purposes. The policy response suggested would be to reduce safe yield to 95 percent and implement demand management during droughts.

Major's analysis of the impacts of climate change on the New York City water system indicated that water demand will increase and supplies will be affected from, for example, saltwater intrusion and demands from other jurisdictions. Consequently, pressures will grow for increased supply sources in the Hudson basin. Planning expertise and knowledge need to be brought to bear to effectively deal with potential climate change.

Wolock's analysis of the Delaware River showed that the frequency of droughts would likely increase, that droughts are more sensitive to changes in precipitation than temperature, and that changes in precipitation make New York City reservoirs particularly sensitive. He also noted that effects of natural climate variability are as significant as those due to possible climate change.

CONCLUSIONS

A number of the participants in the session believed quite strongly that while the region is sensitive to climate change, policy and management measures to accommodate it are possible and in many cases ought to be undertaken now even if climate change does not occur. Among the measures discussed were water conservation programs, drought planning, reservoir storage reallocations, changes in reservoir operations, water pricing policy, water reuse, accepting more risk of water shortage, and potential relaxation of some environmental constraints. In general, many believed that most of the water systems are basically robust and climate change of the magnitudes usually discussed could be accommodated with good management practice.

REGIONAL SENSITIVITY--THE NORTHEAST

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ABSTRACT

Historically, the Corps of Engineers designed reservoirs primarily for flood mitigation, with other benefits as bonus; formal incorporation of multiple uses was a recent modification. Many reservoirs in the Northeast were designed in response to severe hurricane flooding, particularly during the 1960s and 1970s following a period of intense hurricane activity and amid a period of profligate public expenditure. With relatively few hurricanes in recent years, a large number of these reservoirs continue to stand virtually empty, suggesting they might be used to meet increasing demands for water supply. The environmental awareness and fiscal constraints of recent years make it unlikely that many new surface storage facilities will be built, so the existing reservoirs become more attractive. As part of its negotiation with local water authorities, the Corps properly wants to know the incremental flood risk introduced by reallocating some of its flood storage pool for water supply, and how this regional risk is modified by the prospects of global climate change. Our study introduces analytic and numerical techniques to arrive at an optimal reallocation level; for the Colebrook Reservoir on the West Branch of the Farmington River in Connecticut, this turns out to be about 10 percent of the existing flood control pool. We also examine the sensitivity and elasticity of indices of system performance to parameters of climate change, and suggest that the technique be used for regional analysis in the Northeast. In this model, climate change is expressed in the moments of the distributions of hydrologic inputs. Demand for water is unaffected by climate change because we assume that municipal and industrial usage are relatively insensitive functions of climate while irrigated agriculture is negligible in the Northeast, the regional focus of this paper.

INTRODUCTION

This paper deals with how to perform sensitivity analysis using perturbation techniques to increase computational efficiency dramatically. Thus it is primarily a methodological paper, but its thrust is directed at water system managers who feel pressured to offer structural and nonstructural solutions to the perceived need for protection against the impacts of global climate change. Conventional wisdom holds that sensitivity analysis is easily performed by writing f, a scalar quantity to be optimized, as a function of several decision variables (x_1, x_2,...), then calculating the partial derivatives $\partial f/\partial x_i$, and finally evaluating these at the optimum. Usually, the derivatives are estimated by numerical techniques, using finite difference approximations. The function $f(x_1, x_2, \ldots)$ is evaluated, generally by simulation, at the current trial decision point (x). Then each coordinate dimension, or decision element, is systematically perturbed in turn so that a change in the ordinate can be calculated for each change in abscissa. Estimates of these partial derivatives are used to calculate the direction of the gradient leading to the top of the hill; this continues until the optimal solution is identified.

These steps typically require repeated passes through a simulation program. If the system is complicated or characterized by many decisions, or if it is subject to stochastic influences requiring long simulation runs to generate statistically reliable measures of performance, this type of analysis might be infeasible without a supercomputer. Moreover, numerical differentiation is inherently unstable because the numerator is the difference between two numbers often nearly the same size and the denominator typically is small; their ratio is subject to wide fluctuations and stochastic instabilities. Thus, to save computing time and to reduce the risk of unstable results, it would be useful to minimize the number of derivatives to be taken. We show how to do this.

Further difficulties with estimating sensitivities by numerical reckoning of partial derivatives are suggested by a set of linked vectors. We start with the vector u whose elements represent a menu of wholly or partially controllable environmental decisions (reallocating reservoir storage, burning fossil fuels, cutting tropical forests, building flood control dikes, emitting atmospheric lead, etc.). A mixture of these activities produces a range of environmental effects expressed in the vector v, whose elements describe the levels of such processes as increased risk of flood damage, accumulation of atmospheric lead and CO_2, sediment transport, delta aggradation, etc. These effects have environmental consequences contained in the vector w, which includes such items as global and regional changes in temperature and precipitation, local lead exposures, etc. These w-values are thought to induce environmental responses expressed in the vector x, such as changed agricultural response, changed lake levels, changed sea level, changed industrial and municipal demand schedules for water, etc. The x-values evoke regional social and economic consequences y; for example, there might be economic disruption, depression, inflation, hunger, famine, agricultural abundance, epidemic, etc. Finally, the y-consequences might have global reverberations such as hot war, cold war, massive population migrations, major economic restructuring, or even peace; these are grouped as elements of the vector z.

It is common to think of sensitivity as a partial derivative of one of the later links in the causal chain, say an element of y or z, with respect to an earlier link, say an element of u or v. If the mappings from $u \to v \to w \to x \to y \to z$ are known, two forms of analysis are suggested. First, a set of transfer matrices might give the probability density of any vector conditional on the preceding vector in the chain; the analysis resembles a Markov process whose sensitivities can be determined by making repeated trajectories through the system (Monte Carlo analysis). Second, if the transformations are known analytically, a bit of calculus yields the desired sensitivities directly. In a number of environmental cases we examined, the derived theoretical sensitivities were not close to their observed counterparts; lack of predictability is the rule rather than the exception.

What accounts for this disagreement? Sensitivity calculated by stringing together sequences of partial derivatives is simplistic. It ignores terms that tend in expectation to improve the predictions. The over-simplification inheres in the fact that the causal chain does not proceed uniquely from some element of u to some other element of z, as required by the Markov formulation. For example, an action u_1 might be correlated with some other action u_2 and there might be a number of distinct pathways from u_2, by way of elements of v, w, ..., to the target element of z. Thus, changing u_1 changes z directly but also, in expectation, changes u_2, which indirectly changes z. Some intervening elements in the causal chain might be subject to stochastic variation quite independent of other influences in the chain. Some elements might effect changes "downstream" without going through all the intervening links, so that changing u_1 might change x_1 directly without intermediate changes in elements of v and w. All manner of connections and stochastic variations appear in the pattern, as shown by Chen and Fiering (1989). More meaningful than the partial derivative of consequence with respect to cause is the corresponding total derivative that, when expanded in the chain rule of differentiation, requires assessment of several intermediate partial derivatives. When these terms are included, the resulting predicted sensitivities among our examples stand in closer agreement with their observed counterparts.

But, unfortunately, each of these missing terms is itself a derivative and each must be evaluated analytically or by numerical techniques that involve simulation and differencing. This gives rise to more of the numerical instabilities described above, and leads the analyst to wonder whether the optimal solution and estimates of its sensitivity have any validity whatever.

THE PROBLEM IN A WATER RESOURCES SETTING

We now proceed to show how to reduce the number of derivatives required in an optimization scheme for an important class of water resources problems, and how to map potential climate change into parameters of this water resources problem so that reliable sensitivity estimates can be made once the optimum or near-optimum is identified.

We develop the methodology by analyzing a typical case in the Northeast, the focus area for this paper. Consider a gated reservoir designed, built (in 1969), and operated in response to a major hurricane flood. Our study uses Colebrook Reservoir on the West Branch of the Farmington River in southwestern Massachusetts and northwestern Connecticut, for which the Standard Project Flood was the combination in August 1955 of Hurricanes Connie and Diane. They struck within a few days of each other. Connie produced more precipitation on the Farmington watershed than did Diane, but hit after one of the driest summers of record and hence caused less damage than Diane, which struck when natural and man-made storages were full. Their combined effect was catastrophic, with damages estimated at $72 million (1955 dollars). The design flood is estimated to have a return period of about 100 years.

The Hartford Metropolitan District owns the rights to a sizable fraction of Colebrook storage; we are concerned with methodology for resolving the conflict between water supply and flood control uses, and with adapting this methodology to assess the sensitivity of system design with regard to the potential, however uncertain, for climate change in the Northeast. The conflict among claimants to a reservoir has a strong relation to the occurrence of extremes. Indeed, the sensitivity of a region to potential climate change is really a question of sensitivity to hydrologic extremes. And here is the rub! We are asked to make fundamental changes in the planning and operation of our systems, but have so little evidence of the impact of climate change on these critical extreme events.

Colebrook has a capacity of 97,700 acre-feet at spillway crest, with 50,200 acre-feet (51.4 percent) devoted to flood control, 5,000 acre-feet (5.1 percent) to a fish conservation pool, 1,000 acre-feet (1 percent) to dead storage, and the remaining 41,500 acre-feet (42.5 percent) to water supply. This storage allocation vector, and the associated operating rules, are adequate to allow the district to meet its obligation to deliver water to the channel downstream while maintaining a lower constraint for fish and wildlife in the channel at all times. The capacity of the reservoir is 97,700 acre-feet, but the reservoir and the downstream channel flowing full can pass a total of 299,700 acre-feet in any month. If a flood were attenuated so that it passed uniformly throughout an entire month, there would be no downstream flood damage; hence we limit floods to a short duration to model more realistically their hydrographs and to assure the prospect of damaging peaks. Thus the effective flood control capacity of the combined reservoir-channel system is about 139,000 acre-feet.

We use two simple, nonfungible measures of system performance: the probability of flood and the expected value of the square of the deficit from a specified target flow. The first of these measures the frequency of too much water in the system, with no reference to the magnitude of that excess, and for this reason is unrealistic. Moreover, the change in frequency of a true outlier is not necessarily a useful criterion. It is hard enough to estimate that frequency prior to climate change, under conditions of relative stationarity in the climate; it becomes far more difficult to do so under conditions of climate change. The second measure conveys the nonlinearity of the penalty attached to a shortfall. Neither is mapped into dollars or other fungible unit, but if they were and then summed, the optimization problem would be much simpler.

PERTURBATION ANALYSIS

Manufacturing systems often can be shown to be mathematically equivalent to queues with feedback loops. The queue's arrival and departure rates are related to the flux through the plant, and the objective of the analysis is to calculate the number and arrangement of people and machines that confer optimal profit on the operation. It is plausible to think of the size of a water supply reservoir or storage facility as analogous to the number of machines in the manufacturing sequence; more reservoir capacity maps into more buffer storage and hence into more pieces of equipment. More hydrologic input maps into the arrival of more raw materials per unit time, and more output maps into more deliveries from the system. This has been done by a number of workers (Gomez, 1991). Many formal queueing analyses use the Poisson density for arrivals and discharges. However, with only one parameter it is impossible independently to specify higher moments of the input and discharge densities. Our proposed model uses truncated normal distributions to represent each season's hydrologic inputs to the reservoir. Each season's discharge is controlled by an operating rule that meets the seasonal demand rate if enough water is available, and records a deficit otherwise. The sum of squares of all such deficits is normalized to fall within the interval [0,1]; thus it resembles, but cannot readily be combined with, the second performance index (flood probability).

Floods are treated by estimating an instantaneous peak from the average flow during the standard interval; a linear regression with a random additive component was found to be an acceptable estimator in the Farmington study. The operating rule stores the flood volume in the reservoir if possible, with any excess spilled into the channel. A damaging flood is presumed to occur whenever the channel flow exceeds the bank-full capacity.

We now describe the essence of perturbation analysis. Recall that steepest ascent to reach the top of the mountain shares an important feature with sensitivity analysis; both compel the analyst to calculate a significant number of derivatives and to evaluate them at the current point in n-dimensional space. Here *n* is the number of decision variables, and in a typical water resources system this might be very large (Hufschmidt and Fiering, 1966). A total of n+1 simulation runs would have to be made to evaluate these: one at the current point and one along each of the *n* directions or dimensions. These, when properly differenced and divided by the distances Δx_i, would give the *n* partial derivatives from which (1) the gradient (and the next point on the ascending trajectory) and (2) the *n* sensitivities would be calculated. Perturbation analysis allows the calculation of all these *n* partial derivatives with only *one* simulation run provided a few general conditions are met. This powerful result is due primarily to Ho (Ho and Yang, 1986; Ho and Cao, 1991) and depends on the ergodicity of the surrogate queueing system.

A NOTE ON ERGODICITY

The requisite conditions are similar to those required to demonstrate the ergodicity of a stochastic process. A stochastic process is ergodic if its ensemble moments equal its temporal moments. Consider the following example. It is desired to measure the average velocity in a stream, so a ping-pong ball is dropped into the flow and photographed repeatedly as it moves downstream. A long exposure is used so each plate shows a blurred line from which the stream's velocity can be inferred. A number of such photographs are used so that many velocities are estimated over time, and their average is taken; this is the temporal mean. Alternatively, we could simultaneously drop a number of ping-pong balls into the stream and take only one exposure, from which many contemporaneous velocities could be inferred and averaged to give the ensemble mean at one instant. If these two values are equal in expectation, the velocity of the flow process is said to be ergodic with regard to the mean. Ho (Ho and Yang, 1986) showed that only *one* assessment or simulation need be run to calculate *all* the partial derivatives at the point.

It is necessary first to assure that the abstraction or queueing model does no violence to the real system, and also to demonstrate that ergodicity holds. If so, the perturbation analysis algorithm can take control of the calculation and, more or less mechanically, assess the partial derivatives in all directions. Our case study deals with the sensitivity of the optimal reallocation of flood control storage in an existing reservoir with respect to (the hydrology parameters affected by regional) climate change, although sensitivity with respect to any other element of a more complicated system could be calculated.

We tested the adequacy of our queueing model by running enormous numbers of iterations of a standard simulation program and calculating the sensitivities by brute force. For some of our derivatives we made as many as 100,000 replications on a Cray supercomputer, and we compared the averages of these derivatives ("ground truth") to the values computed by perturbation analysis. The results were so gratifyingly close as to be startling; no sensitivities or elasticities (ratios of sensitivities) disagreed by more than a few percent.

APPLICATION TO COLEBROOK

Trial simulation runs at 1,000, 10,000, and 100,000 years showed rapid convergence of the sensitivities of flood performance indices at 1,000 years, beyond which not much was learned about system performance with regard to floods. But at least 10,000 years were required for convergence of the deficit measure. This confirms that higher power measures (i.e., squared values versus linear probability terms) require more replication for guaranteed stability. Table 1 shows the agreement at the 1 percent confidence level; that is, the range of values at the 1 percent confidence level for the perturbation analysis sensitivities falls within that range for the brute force experiments. As expected, some of the smallest sensitivities do not meet this objective, but we believe this can be traced to the numerical instabilities discussed earlier. In Table 1, derived for a two-season model, μ_i is the mean arrival rate in season i, σ_i is the standard deviation, λ_i is the discharge rate in season i, $\rho_{i,j}$ is the lag-one serial correlation coefficient between flows in time periods i and j, and $C = 3$ is the allocation for water supply (where the total available capacity of the reservoir, earlier shown to be 138,907 acre-feet, is scaled for convenience to $K = 10$ volume units).

Lacking a scalar objective function, we set the current standards of reservoir performance as targets and systematically vary the water supply storage, C, with capacity K fixed, to determine at what level of C the current performance standards are violated. Thus we attempt to operate the reservoir more prudently so that C can be increased without incremental flood risk. Thereafter we increase C further, inducing additional risk, and quantify the enhanced water supply benefits by noting the reduction in the deficit index. Finally, we solve the problem again under new values of the inflow parameters such as might be attributed to climate change. This differs from the customary approach to studying the water resources effects of climate change, which simulates system performance under new hydrology without specific exploration of the sensitivities and elasticities at the margin. This new information, which had been available in complicated systems only at great computational expense, is now more readily available with perturbation analysis. Moreover, climate change is not a step function but will come about, if at all, through continuous variation, and the required sensitivities can now be obtained far more efficiently.

Figure 1 shows the essential results. The abscissa is the water supply allocation, C, in thousands of acre-feet, with step sizes of 5×10^3 acre-feet. The two curves show the increase in (summer or hurricane season) flood risk as the water supply pool ranges from 26,500 acre-feet to 71,500 acre-feet, with a simultaneous decrease in the normalized penalty for water supply deficit. These boundaries are based on the observation that at 26,500 acre-feet there are no floods in any of the seasons, while above 71,500 acre-feet we sustain an increasing flood risk with no improvement in water supply performance. The current allocation scheme corresponds to $C = 41,500$ acre-feet. Each run of 10,000 years requires about 50 seconds of Cray CPU time. With a scalar objective function these curves could be mapped into a composite response over the range of C, whereupon the optimal specification would be made.

Performance measures were calculated both by simulation and by sensitivities estimated by perturbation analysis. We experimented with increased values of the water supply demand and inflow moments. Over a large range of flood probabilities the values agreed to within 6 percent. Agreement remained close for all cases up to a 10 percent increase in the release requirements, a 5 percent change in the mean inflow, and a 10 percent decrease or 15 percent increase in the standard deviation of the inflow. We applied these changes uniformly to all seasons of the model, even while recognizing that most GCMs do not suggest this pattern of climate change in the Northeast.

Table 1.

Verification of Seasonally Varying Performance Measure Model

Sample Results

Parameter Values: $\mu_1 = 8, \sigma_1 = 1.5, \lambda_1 = 0.5, C = 3, \rho_{1,2} = -0.6$

$\mu_2 = 6, \sigma_2 = 2, \lambda_2 = 0.5, C = 3, \rho_{2,1} = -0.6$

Performance Measures: Pr[Flood1] = 0.6307 E[Deficit^2] = 0.0000

Pr[Flood2] = 0.2265

	Perturbation Analysis Estimate		Brute Force at 1%	
	Mean	Range	Mean	Range
$\frac{\partial Pr[Flood1]}{\partial C}$	0.2517	0.2517 to 0.2517	0.2519	0.2388 to 0.2650
$\frac{\partial Pr[Flood1]}{\partial \mu_1}$	0.2517	0.2517 to 0.2517	0.2519	0.2437 to 0.2601
$\frac{\partial Pr[Flood1]}{\partial \mu_2}$	0.0008	0.0007 to 0.0009	0.0001	0.0000 to 0.0002
$\frac{\partial Pr[Flood1]}{\partial \sigma_1}$	- 0.0837	- 0.0837 to - 0.0837	- 0.0845	- 0.0935 to - 0.0755
$\frac{\partial Pr[Flood1]}{\partial \sigma_2}$	- 0.0024	- 0.0027 to - 0.0022	- 0.0003	- 0.0007 to 0.0001
$\frac{\partial Pr[Flood1]}{\partial \lambda_1}$	- 0.2517	- 0.2517 to - 0.2517	- 0.2535	- 0.2807 to - 0.2264
$\frac{\partial Pr[Flood1]}{\partial \lambda_2}$	- 0.0008	- 0.0009 to - 0.0007	0.0000	0.0000 to 0.0000
$\frac{\partial Pr[Flood2]}{\partial C}$	0.1506	0.1506 to 0.1506	0.1507	0.1428 to 0.1586
$\frac{\partial Pr[Flood2]}{\partial \mu_1}$	0.0000	0.0000 to 0.0000	0.0000	0.0000 to 0.0000
$\frac{\partial Pr[Flood2]}{\partial \mu_2}$	0.1506	0.1506 to 0.1506	0.1504	0.1441 to 0.1567
$\frac{\partial Pr[Flood2]}{\partial \sigma_1}$	0.0000	0.0000 to 0.0000	0.0000	0.0000 to 0.0000
$\frac{\partial Pr[Flood2]}{\partial \sigma_2}$	0.1129	0.1129 to 0.1129	0.1134	0.1027 to 0.1239
$\frac{\partial Pr[Flood2]}{\partial \lambda_1}$	0.0000	0.0000 to 0.0000	0.0000	0.0000 to 0.0000
$\frac{\partial Pr[Flood2]}{\partial \lambda_2}$	- 0.1506	- 0.1506 to - 0.1506	- 0.1502	- 0.1725 to - 0.1279

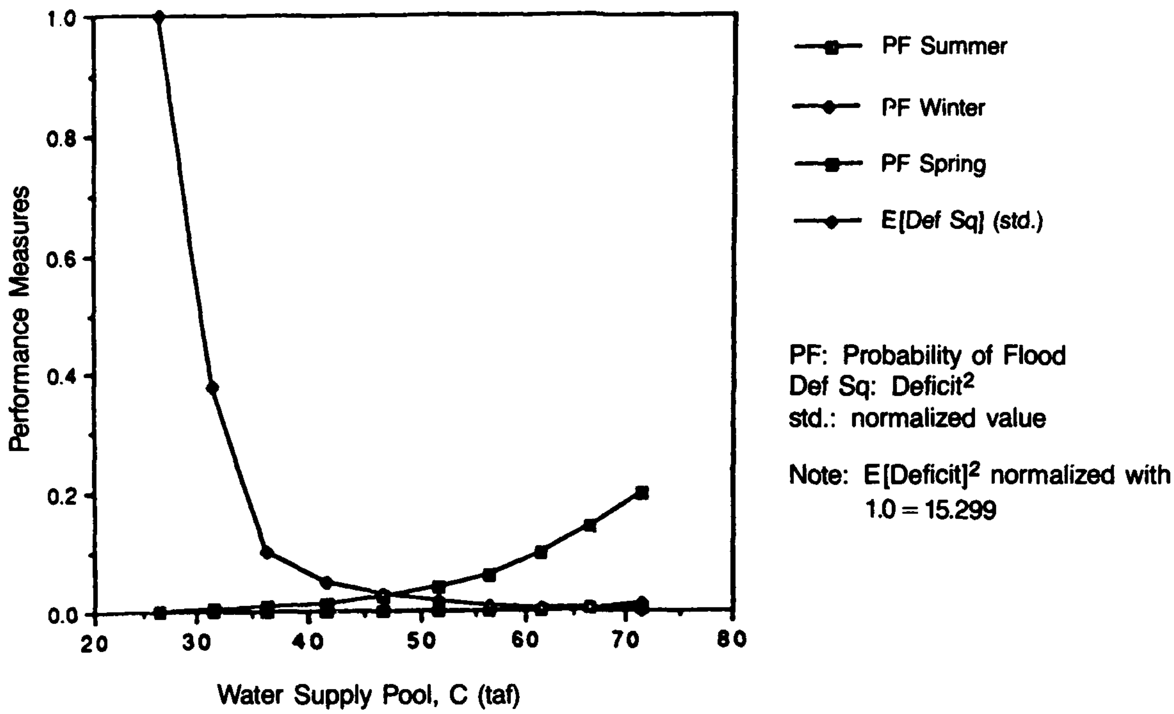

Figure 1. **Performance measures versus water supply pool.**

It was expected that the first-order approximations using perturbation analysis for the deficit penalty would show poorer agreement with brute force results than with flood probability; this turned out to be the case. In particular, the same 6 percent spread in output was obtained up to a 5 percent increase in release requirements, a 5 percent decrease or 3 percent increase in the mean inflow, and a 3 percent increase in the standard deviation of the inflow. Figures 2 and 3 show the sensitivities of the performance measures with respect to release requirements; other graphs could be presented to show the range of sensitivities to the several parameters of the problem.

Formal optimization of the allocation of reservoir storage would require a single-valued objective function that combines all the performance measures or an explicit multi-variate analysis as in Keeney and Raiffa (1976). Failing this, our alternative sets the current standards of reservoir performance for flood control and water supply as targets. Figure 4 treats this issue. The axes are water supply and spring flood performance measures, which can be traded as C is varied. The figure helps identify promising combinations. As noted, we selected the current allocation point, $C = 41{,}500$ acre-feet, and two additional trial points for further analysis: $C = 46{,}500$ acre-feet (sell about 10 percent) and $C = 51{,}500$ acre-feet (sell about 20 percent of the available flood storage). For $C > 51{,}500$ acre-feet, the elasticities of flood probabilities with respect to C nearly triple, whereupon for $C > 51{,}500$ acre-feet the flood risk is deemed unacceptably large. In addition to sensitivities related to C, we calculated sensitivities with respect to the downstream release requirements.

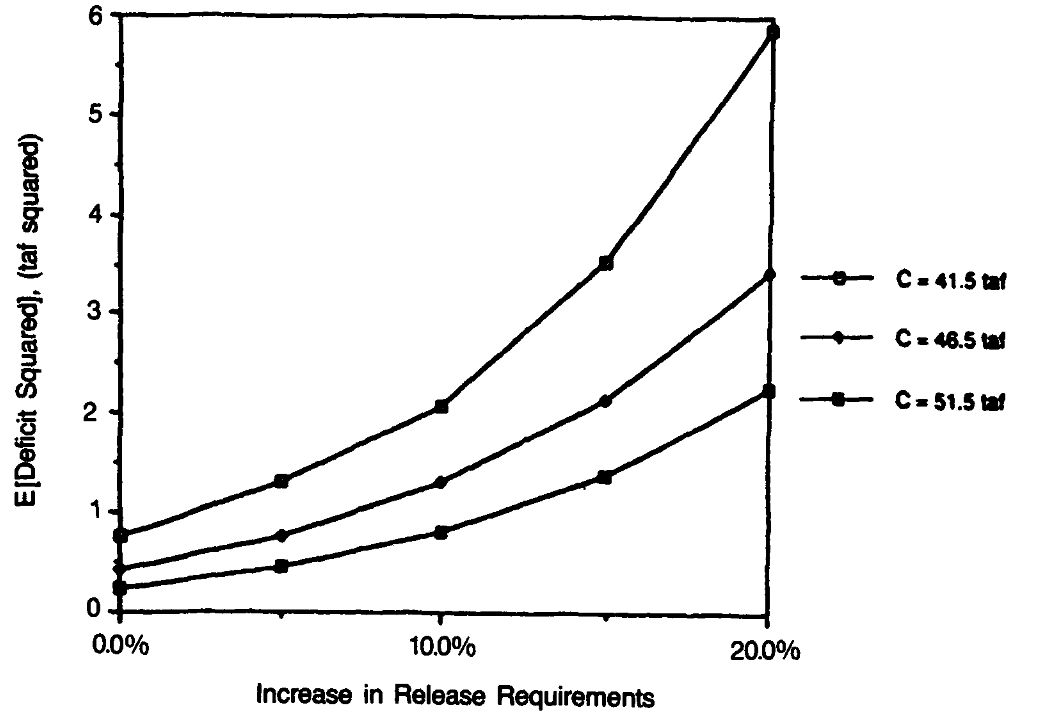

Figure 2. **E[Deficit²] versus percentage changes in release requirements.**

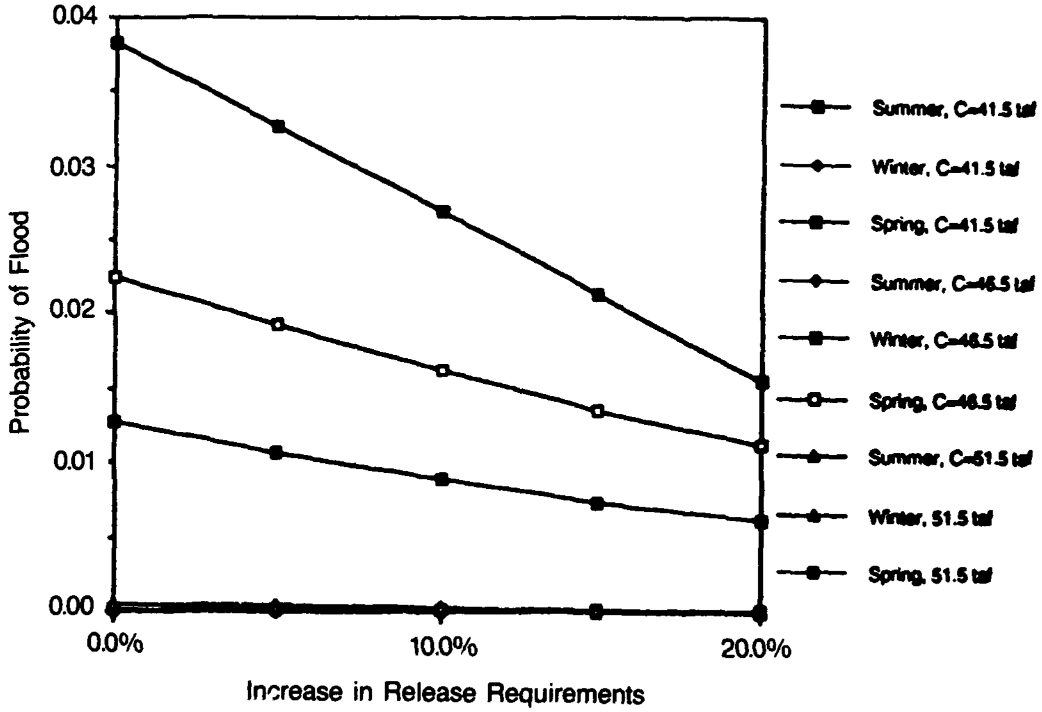

Figure 3. **Probability of flood versus percentage changes in release requirements.**

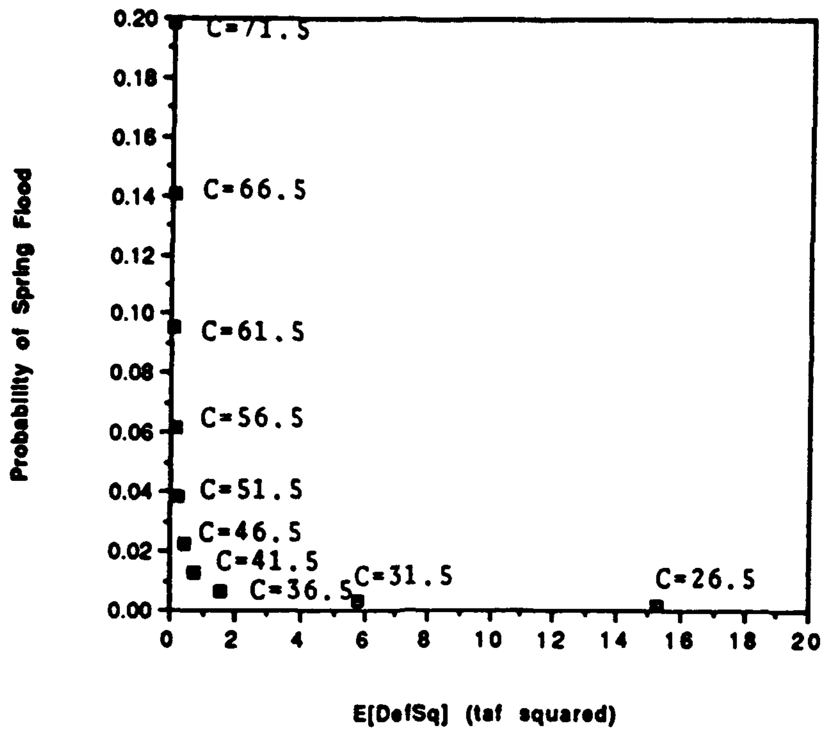

Figure 4. **Probability of spring flood versus E[Deficit^2].**

THREE RESERVOIR ALLOCATION ALTERNATIVES AT COLEBROOK

Under the current allocation at Colebrook Reservoir, Case I or C = 41,500 acre-feet, a 20 percent increase in release rates in each season leads to a 670 percent increase in the deficit index; a 5 percent increase in release requirements leads to a 70 percent increase in the index. At the same time, the 20 percent increase in release requirements halves the flood probability. If additional storage cannot be obtained from the Corps at Colebrook, the Hartford authorities should modify their rules to offset those penalties associated with increasing demands.

Under Case II, with the sale of 10 percent of the available flood storage space, we have C = 46,500 acre-feet, at which point a 5 percent increase in release requirements for each season generates the same level of performance as for Case I. If the release rate grows by 20 percent the deficit penalty index will triple, which is less than half of its 670 percent increase in Case I. Spring flood probabilities will nearly double to about 0.0225 per year, which might be deemed acceptable. In fact, if changes in operation were adopted, the Case II allocation would tolerate a 17 percent increase in release rates without change in either performance index.

Finally, for Case III we sell 20 percent of the flood storage space and set C = 51,500 acre-feet. Release rates can increase by as much as 9 percent without affecting the performance indices, and changes in the operating policy could support a 15 percent increase in release rates with no effect on performance.

CLIMATE CHANGE AT COLEBROOK, AND GENERALIZATIONS TO THE REGION

Perturbation analysis makes it easy to study the effects of climate change on the Colebrook system. In an earlier study that addressed these same questions, Schwarz (1977) anticipated that the major impact of climate change on water resources in the Northeast will come from the first three moments and the persistence of the inflow distribution; here we examine the effects of only the first two. It is plausible that the mean and standard deviation of input distributions would vary by as much as 20 percent under the influence of climate change. Conventional techniques for studying this range of parameter variation would require a very large number of expensive simulation runs. The requirement is rendered much less formidable by use of perturbation analysis, which efficiently exploits a single simulation. Figures 5 and 6 show the effects of changes in the mean inflow on the two performance indices for all three cases, and Figures 7 and 8 show the effects of changes in the standard deviation. These latter changes appear to cause less dramatic effects on the probability of flood than on the deficit index; as indicated earlier, the nonlinearity of the deficit index makes this result plausible. However, it should be noted that the economic and social penalties associated with these physical manifestations of system inadequacy can sharply alter this relationship. Regret analysis as suggested by Matalas and Fiering (1977) (and subsequently by others) is the preferred method of analysis for this problem.

The water supply storage level at Colebrook, C = 41,500 acre-feet, appears inadequate to meet increasing demands for water supply; significant increases (of about 70 percent) in the deficit index would result from as little as a 5 percent increase in demand. If 5,000 acre-feet were transferred from flood control to water supply storage, the current standard of performance could be maintained under a 5 percent growth in demand; transfer of 10,000 acre-feet from flood control would allow demand to increase by about 9 percent. However, these increases in water supply storage would necessarily increase the flood probabilities. While these increases could be mitigated by modified operating policies, there is still the question of the acceptability of the new level of flood risk.

Flood probabilities are increased by an increase in the mean inflow at Colebrook; for the current allocation, C = 41,500 acre-feet, a 20 percent increase in the mean inflow produces what we consider *a priori* to be an unacceptably high flood probability of 0.07. If 10,000 acre-feet are transferred from flood storage, as little as a 5 percent increase in mean flow raises the flood probability to more than 0.05. An intermediate level of transfer, 5,000 acre-feet, retains a flood risk more or less equal to that of the current allocation. Increases in the standard deviation are held to be more likely than decreases in that statistic; these will significantly raise the deficit index while adversely affecting the flood probability. Changes in the standard deviation do not offer a potential tradeoff: increases reduce all of our performance indices.

Therefore we recommend for Colebrook Reservoir that a staged transfer of flood storage be undertaken. The initial reallocation should be 5,000 acre-feet. In the absence of palpable climate change during the useful life of the reservoir, the operating policy can be modified to offset increases in the flood probability attributed to the loss of storage. While the same general statement can be made for a transfer of 10,000 acre-feet in the absence of climate change, the system would be exposed to unacceptably high risks in the event of such climate change as would be expressed in small changes in the mean and standard deviation. If all or part of the transfer of 10,000 acre-feet could be reversed, it might be appropriate to transfer the entire amount. However, the political process would not view favorably the prospect of reversal, so we recommend the smaller transfer.

In the humid Northeast, water resources decisions are not driven by small changes in the lower moments of inflow distributions; we do not rely on irrigation schedules and snowpack storage to meet carefully calculated contractual needs throughout long dry periods. Our water resources designs are driven by extremes, typically by hurricane floods. The pressures consequent to inexorably growing populations are likely to change slowly enough to allow adjustments and accommodations (*cf.* Rogers, 1987), while the real economic, hydrologic, ecological, hydraulic, and geomorphologic threats are embedded in the extremes. But, alas, apart from some very sketchy relationships posited for the frequency of hurricanes, there is little credible evidence for establishing defensible

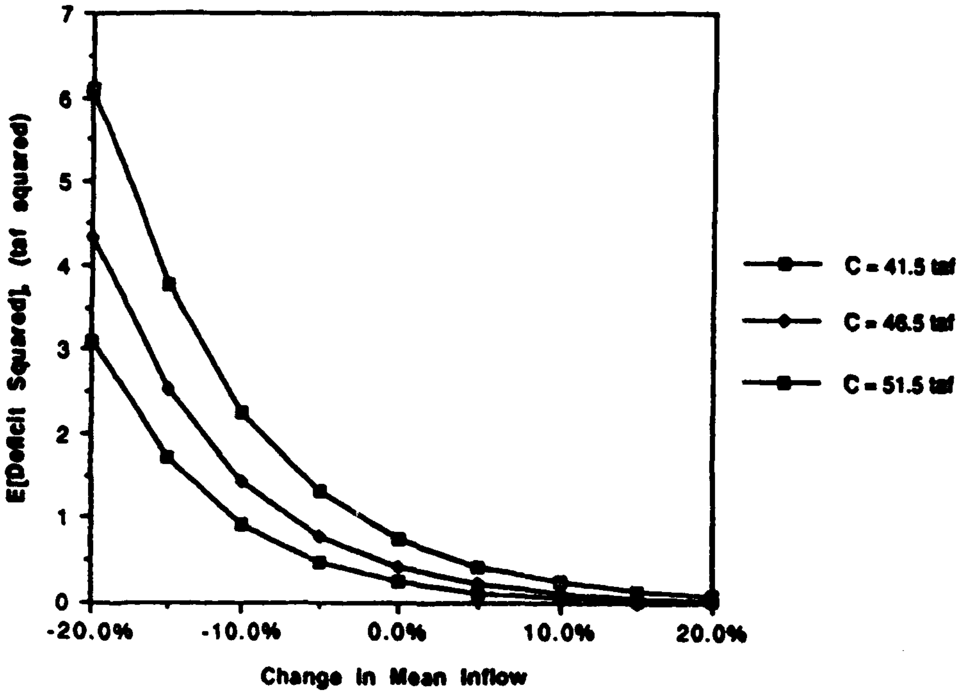

Figure 5. **E[Deficit²] versus percentage changes in mean inflow.**

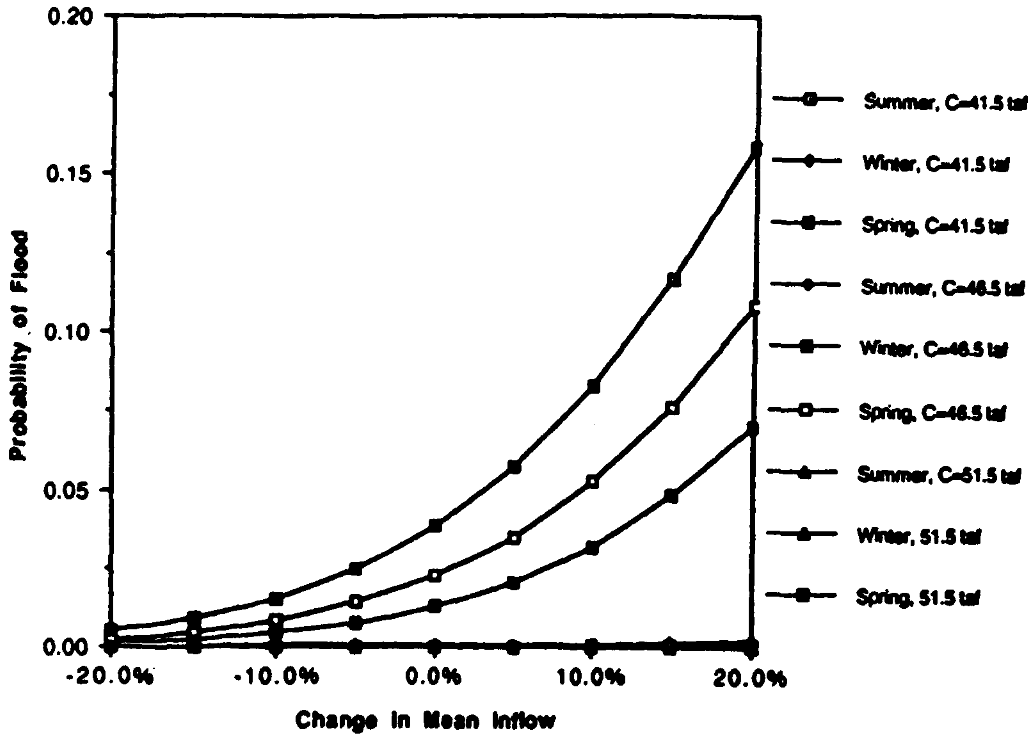

Figure 6. **Probability of flood versus percentage changes in mean inflow.**

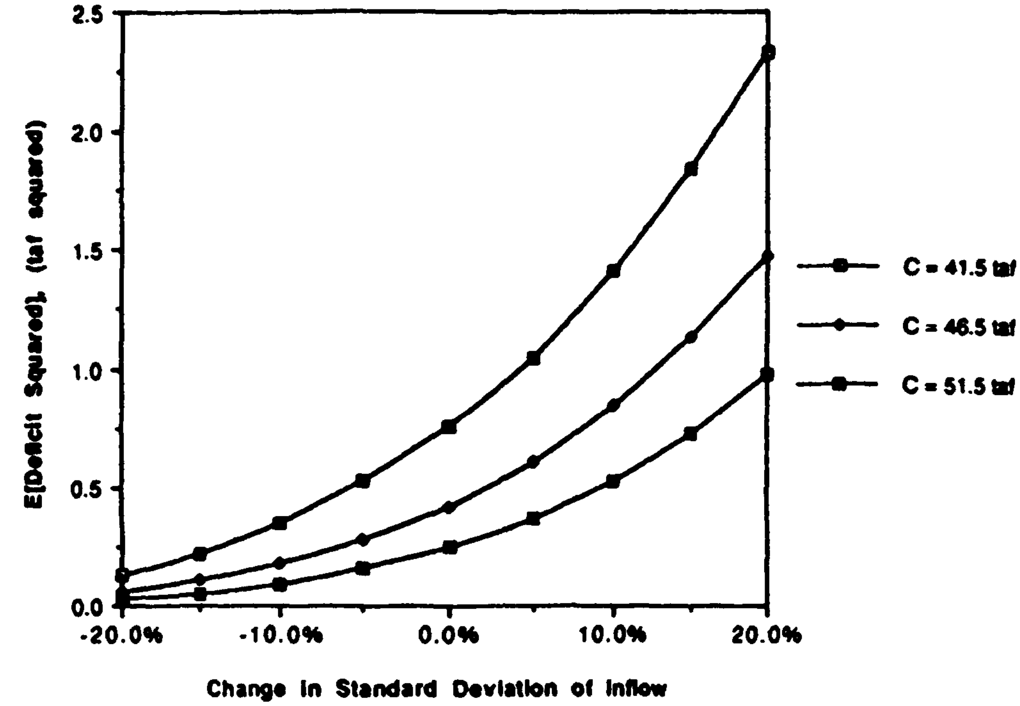

Figure 7. **E[Deficit²] versus percentage changes in standard deviation of inflow.**

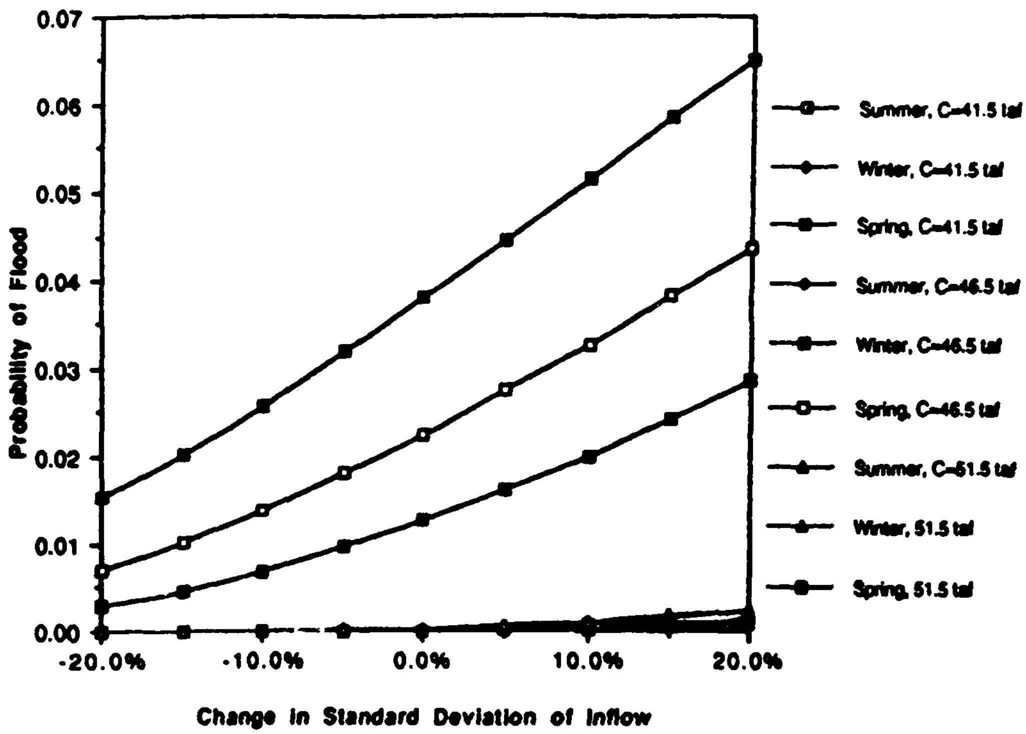

Figure 8. **Probability of flood versus percentage changes in standard deviation of inflow.**

relationships between climate change and hurricane frequency and intensity. So we recommend that it appears prudent to muddle through, again relying on our inherent ability to adapt in a region that appears little threatened by the predicted rigors of climate change.

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POTENTIAL IMPACTS OF CLIMATE CHANGE UPON THE WATER SUPPLY OF THE BOSTON METROPOLITAN AREA

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ABSTRACT

This is a study to investigate the possible impacts of climate change upon the reservoir-based water supply system of the Boston metropolitan area operated by the Massachusetts Water Resources Authority (MWRA). Demand is below safe yield only because of aggressive demand management.

Using a conceptual hydrologic model, the Penman-Monteith equation, to estimate potential evapotranspiration, and the Penman equation for reservoir evaporation, time series of both streamflows and reservoir evaporation losses corresponding to possible scenarios of climate change were developed. The scenarios were derived from general circulation models (GCMs) and a sensitivity analysis of temperature and precipitation changes. Using the MWRA's safe yield computer model, the safe yield corresponding to each scenario was then determined.

The results show serious decreases in average streamflow and yield due to the scenarios of the GCMs, temperature increases alone, and increases in growing seasons. In addition, the peak flow occurs earlier than in the present climate because snowmelt occurs sooner and the low-flow season has less flow and extends longer. If precipitation is also decreased, the impacts are even more severe. Impacts are mitigated if there are increases in precipitation (unlikely in the Northeast) or canopy evapotranspiration resistance increases due to enriched CO_2 (which may or may not occur). The decreases in reservoir yield occur not only because there is less streamflow, but also because flow maintenance requirements result in less of the flows being available. Further work in the study will include applying more scenarios and investigating the impacts of climate change on water demand. Additional work will also include working with the MWRA to develop short- and long-term policy responses to attempt to mitigate or adapt to possible climate-change impacts.

INTRODUCTION

Many scientific sources are predicting global warming and climate change due to a variety of factors. Major concerns include the potential impacts upon water resources and how society might respond to them. A series of studies sponsored by the U.S. Environmental Protection Agency (EPA) for the southeastern, western, and central parts of the United States has been completed and reported in Smith and Tirpak (1989).

A similar case study is being conducted in the northeastern United States on the possible impacts of climate change upon the reservoir-based water supply system serving the Boston metropolitan area. This system is particularly interesting to study because only through an aggressive demand-management program (e.g., water conservation, leak control, and public education) has the MWRA been able to bring demand below safe yield of the reservoir system. Future safe yield information is critical to the MWRA in planning for additional demand management or water supply augmentation activities.

For this climate-change impact study, a conceptual hydrologic model was calibrated and verified for the reservoirs' watersheds. Streamflows resulting from scenarios of possible climate-change impacts upon precipitation, temperature, and other parameters were then determined. Using the MWRA's Safe Yield computer model, the safe yields corresponding to each scenario then were determined. In a later study, policy options for the MWRA to respond to the potential changes will be developed with MWRA staff.

STUDY AREA

Introduction

Boston, its neighboring communities, and some communities in central Massachusetts receive water supply from the MWRA, an independent public authority created by the Massachusetts legislature. The service territory includes 46 communities and 2.4 million people. In 1987, water demand was 336 millions of gallons per day (mgd). Through an aggressive leak-detection and repair and demand-management program, by 1989 average demand was decreased to under 290 mgd. The MWRA anticipates that with the expansion of these programs, demand will remain at 300 mgd for the next 10 years or possibly 30 years. Without expansion of these programs, demand could grow to 340 or 350 mgd by the year 2020.

Water Supply System and Operation

The main sources of supply for the MWRA are the Quabbin and Wachusett reservoirs, located in central Massachusetts and shown in Figure 1. From these reservoirs, water flows east under gravity to the distribution system in the Boston metropolitan area. There are also several reservoirs used for emergency supply.

Quabbin Reservoir is located on the Swift River. It collects water from 186 square miles of Swift River drainage as well as water transferred to the reservoir from the Ware River watershed by the Quabbin Aqueduct (see additional information below). The storage volume of Quabbin is 412 billion gallons.

Quabbin has a minimum downstream flow release to the Swift River of 20 mgd. During the months of June through November, the minimum is increased to 45 mgd if the flow on the Connecticut River (to which the Swift River is tributary, see Figure 1) at Montague is less than 4,900 cubic feet per second (cfs). The minimum release is increased to 71 mgd if the Montague flow is below 4,650 cfs. The average flow at Montague during this period is 7,421 cfs.

Water diverted from the Ware River, the next river basin to the east of the Swift River basin, can be transferred either to Quabbin Reservoir or Wachusett Reservoir. The decision is based upon the time of year and storage in each reservoir. The diversion structure controls 96.8 square miles of the Ware River basin. Water may only be taken during the period of October 15 through June 14 when the flow exceeds 138.5 cfs. This is referred to as flood skimming. The average monthly flow of the Ware River during this period is 229 cfs.

Wachusett Reservoir receives inflow from the Nashua River watershed and water transferred from the Ware River. Its storage volume is 65 billion gallons. It also has a minimum daily release.

Hydrology

The U.S. Geological Survey (1985) reports the average annual precipitation over the Swift and Nashua watersheds is approximately 42 inches. It is distributed relatively evenly throughout the year. There is snow from

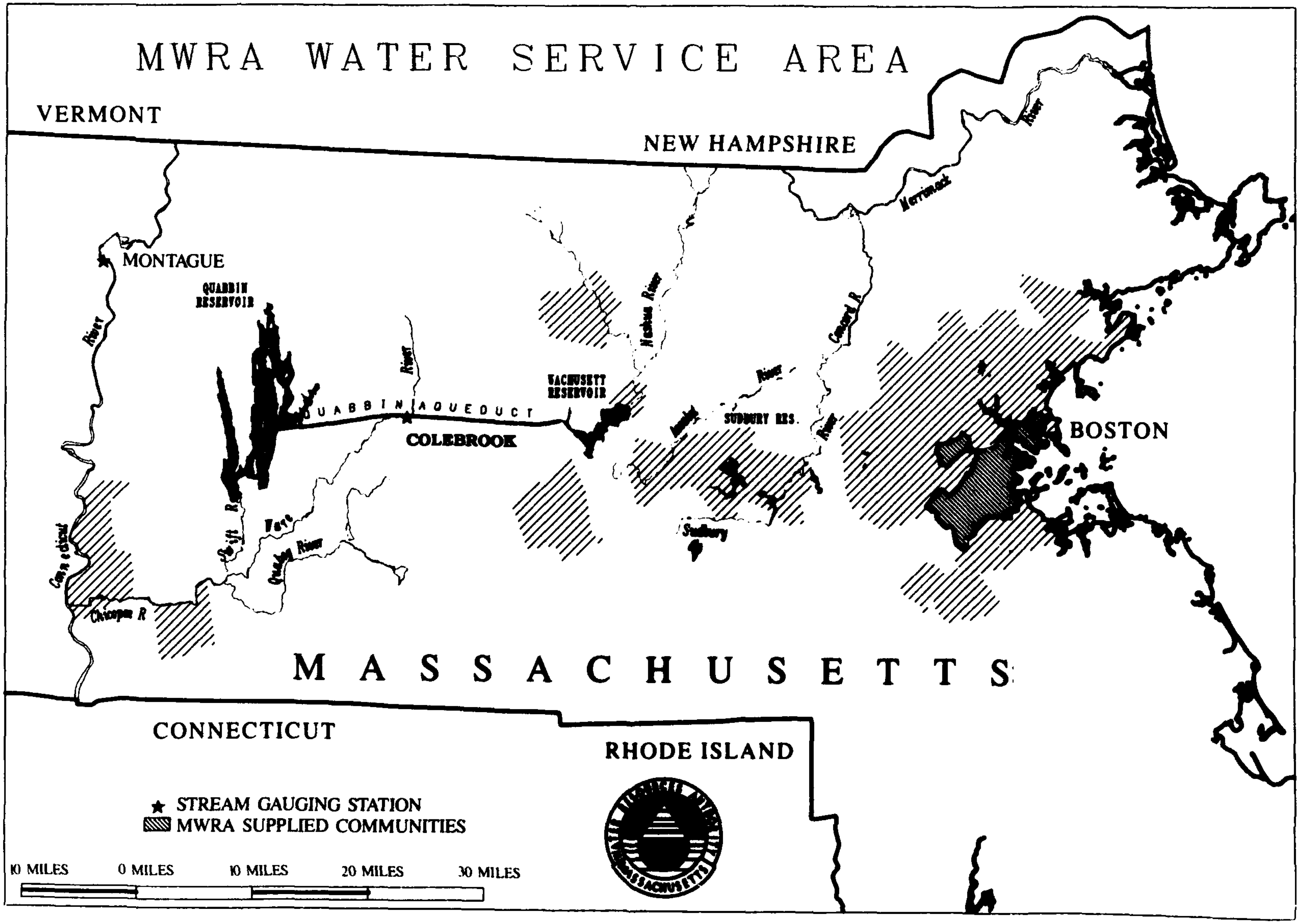

Figure 1. **Study area.**

approximately December through March. The average annual runoff is reported to be approximately 23 inches, with a peak flow in the spring from snowmelt (see base case, Ware River hydrograph, Figure 2). Similar conditions exist for the Connecticut River basin.

SAFE YIELD MODEL

Introduction

The MWRA's safe yield model is described by MWRA (1989). It uses reservoir simulation techniques to determine the annual (or "safe") yield that can be supplied from the MWRA water supply system over a critical hydrologic period with a specified reliability. The model functions on a monthly time step; during each time step the model reads the streamflows entering the system, calculates net reservoir volume changes due to precipitation and evaporation, determines minimum flow release requirements from Quabbin Reservoir based upon streamflow at Montague, and determines the amount of flood skimming permissible from the Ware River. Then, based upon reservoir operating policies, reservoir volume balances are calculated and a determination is made as to whether that month's demand can be met. The reservoir volumes are then adjusted to reflect the amount of demand supplied. If the entire monthly demand cannot be met, a failure is recorded. The system reliability is measured by the ratio of successful supply months to the total number of months simulated.

At the option of the user, the model can also simulate drought management scenarios. Under these scenarios, if the desired monthly demand cannot be fully supplied because of a shortage of water, the monthly demand is decreased by an amount based upon the combined reservoir storage. If the decreased demand cannot be met, then a failure is recorded.

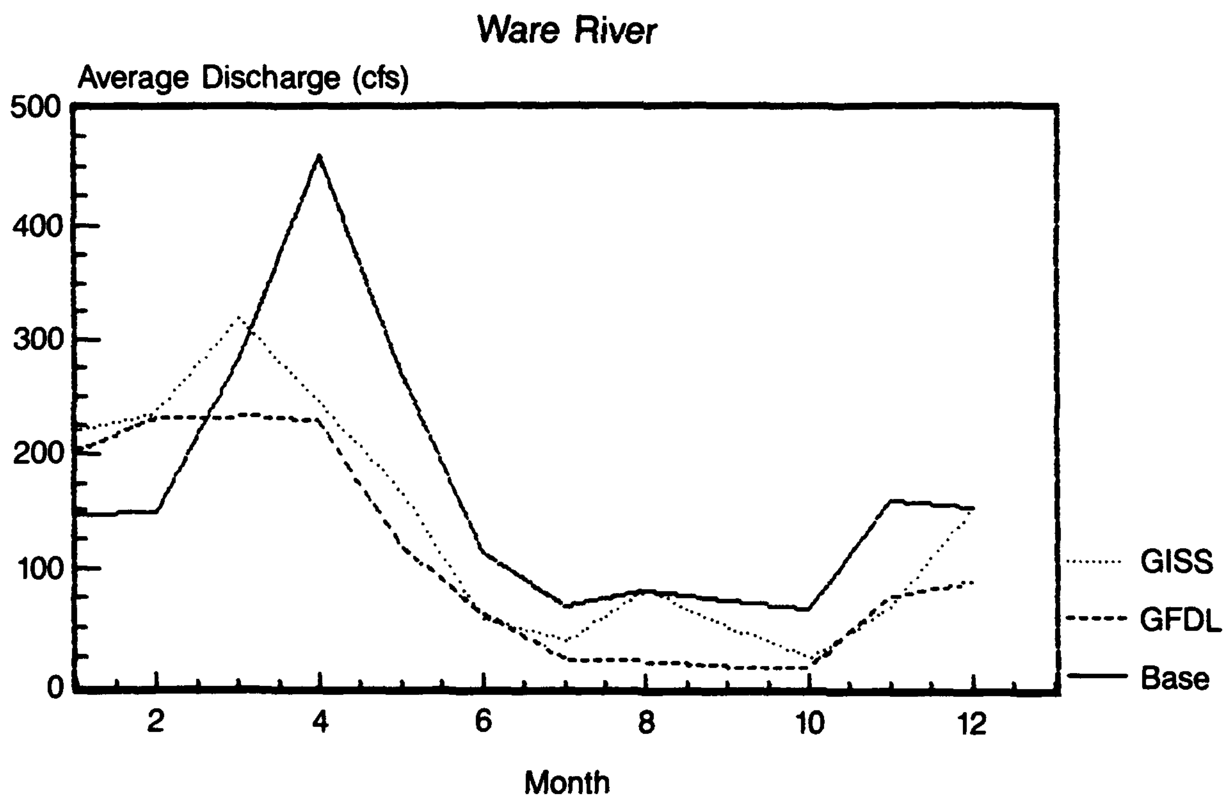

Figure 2. **Ware River average monthly discharge.**

Data Requirements

In the safe yield model, monthly demand is specified as a percentage of the average annual demand. Generally, in using the model for studies, the MWRA relies on historical hydrologic data for the period 1930 to 1979. These include monthly precipitation on the reservoirs, monthly streamflow of the Ware River at Colebrook (to estimate monthly streamflows into the Quabbin and Wachusett reservoirs using ratio of drainage areas), the number of days each month during flood-skimming months that water can be transferred from the Ware River to reservoir storage, the possible monthly volume that can be transferred from the Ware River, and the minimum flow release requirements from Quabbin Reservoir based upon the flow of the Connecticut River at Montague. The latter three inputs are determined by pre-processing the historical daily flow data for the Ware and Connecticut rivers to model the impacts of the flood-skimming and low-flow requirements. Monthly evaporation from the reservoirs is also a data requirement (the same value is used for each reservoir; it is the long-term monthly average).

Since in this study streamflows were simulated on a monthly basis (see later section on the runoff model), regression and curve fitting were used to develop relationships between the possible monthly skim volume and the Ware River monthly discharge, between the possible number of transfer days and the discharge, and between the Quabbin low-flow release and the Connecticut River flow. These were done by using daily historical data on flows to determine the monthly skim volumes and days, and low-flow requirements and then fitting them against the monthly flow discharges.

CALIBRATION AND VERIFICATION OF RUNOFF MODEL

Introduction

As described in the safe yield model section, it is necessary to be able to simulate the streamflows of the Ware River at Colebrook (the location of the transfer intake structure) and the Connecticut River at Montague. A conceptual runoff model with climate input data on precipitation, temperature, and potential evapotranspiration was calibrated and verified for each location. Then changed values of these variables corresponding to possible climate-change scenarios were used in the runoff model to simulate possible impacts upon streamflow.

Rainfall-Runoff Model

The rainfall-runoff model consists of two major modules, the National Weather Service River Forecast System (NWSRFS) snow accumulation and ablation model (Anderson, 1973) and the Sacramento soil moisture model (Burnash et al., 1973). Each module is a conceptual model describing in some detail the appropriate hydrologic processes. Each module is well known and used in operational and research hydrology.

The snowmelt model uses an energy balance approach to calculate snowmelt during rain-on-snow periods and a temperature index approach during nonrain periods. The input data used by the model for each time step (24 hours in this application) are temperature and precipitation. The model internally determines the areal-extent, water-equivalent, and heat deficit of the snowpack at each time step, and the resulting melt and rain in the sub-basin.

The Sacramento soil moisture model represents the passage of the daily rain and melt over the soil surface or through the soil into water bodies such as rivers (as in the case of the snow model, the time step for the soil moisture model was 24 hours). It effectively models direct runoff, interflow, and slower responding base flow. Evapotranspiration is possible from both upper and lower soil layers. The output of the model is runoff.

Once the runoff is known, it must be routed down the stream channel. Since the time of travel in both the Ware and Connecticut River basins is on the order of days and the time step for the safe yield model is 1 month, flow routing of the runoff was not performed for either basin. Instead, the runoffs were aggregated monthly and used as the monthly streamflow values in the safe yield model.

Calibration and Verification

The EPA requested the project team to use the period 1950 to 1980 as representative of hydrologic conditions before potential climate change. Therefore, data from this period were used to calibrate and verify the runoff model for both the Ware and Connecticut rivers. There are USGS gauges at Colebrook, the location of the Ware River diversion, and at Montague on the Connecticut River.

An 11-year period (1960-1970) covering a range of hydrologic conditions was chosen to calibrate the model and a different 10-year period was used to verify the model. In each case, there was a "warm-up" period of 3 years starting in May (when there is no snow on the ground) before the start of the calibration or verification simulation run to set the initial groundwater storage values. The results of the calibration and verification for both locations were satisfactory.

As a final check, the period 1950-1979 was simulated to obtain base-case flows, which were compared to the historical measured flows. In addition to using daily values of historical precipitation and temperature, monthly values of potential evapotranspiration for the growing season were determined using the Penman-Monteith evapotranspiration model (see next section) and historical monthly values of temperature, wind speed, sunshine, and relative humidity. The Penman-Monteith model had been calibrated with the monthly values of potential evapotranspiration determined from the initial calibration of the runoff model. As can be seen in Table 1, the streamflow time series agree well; therefore, the model reasonably represents monthly flows in both the Ware and Connecticut rivers.

Table 1.

Comparison of Historical and Simulated (Base Case) Time Series for Present Climate

Time Series	Mean (cfs)	Std. Dev (cfs)	Skewness
Ware Hist.	169.2	148.3	1.4
Ware Simul.	169.0	166.8	1.5
Correlation Coefficient between Hist. and Simul. = 0.8118			
Conn. Hist.	14550.	11810.	1.5
Conn. Simul.	14029.	11852.	1.7
Correlation Coefficient between Hist. and Simul. = 0.8451			

Use of Base-Case Flows in Safe Yield Model

A final check on the calibration and verification procedures was to compare the results of the safe yield model using historical streamflow data for the period 1950-1979 to the results using the base-case flows. The values of the safe yield at the 98.5 percent reliability level matched closely; they were 294 mgd with historical data and 306 mgd with the base-case flows. Other parameter values such as minimum flow releases and water transfers also agreed well. Therefore, the project team had confidence that the modeling procedures provided adequate representation of the flows in the river basins and of system safe yield.

POTENTIAL EVAPOTRANSPIRATION AND EVAPORATION

The Penman-Monteith (Monteith, 1965) energy budget method was employed to estimate potential evapotranspiration (Et). Potential (free-surface) evaporation (Ep) was estimated with the Penman equation.

The Penman-Monteith energy budget method was chosen because the model is composed of a number of the general circulation model prognostic variables; thereby lending itself to easy perturbation by climate-change scenarios. The model is also derived from the physical conservation equations and therefore is generally considered to be universally applicable.

Except for the canopy resistance term (rc), parameter values were determined to be either constants or functions of air temperature, wind speed, solar radiation, and the saturation vapor pressure deficit. Surrogates of solar radiation were empirical clear-sky estimates of solar radiation combined with observed cloud cover or percent of possible sunshine. Saturation vapor pressure deficit was estimated from air temperature and relative humidity. Historical values of temperature, wind speed, percent of possible sunshine, and relative humidity for several climate stations in the study area were used to generate time series of Et and Ep for the period 1950-1979.

Few measurements exist for rc. Furthermore, the focus of these efforts has been on estimating rc or related variables for irrigated crops, such as alfalfa. In addition, some parameter was needed to adjust the Penman-Monteith model to agree with the monthly Et values used in the runoff model and to account for theoretical and data inadequacies in the Penman-Monteith model. Therefore, it was decided to adjust the monthly value of rc so that the long-term monthly average of the daily Penman-Monteith model simulations for Et using historical data agreed with the monthly values of Et determined in the calibration of the runoff model during the growing season (April through October for the Ware basin, May through October for the Connecticut basin). As a check on this procedure, the monthly values of rc determined for both the Ware and Connecticut basins were within one or two orders of magnitude of the diverse values reported in literature. As described earlier, the values of Et used in the runoff model for the nongrowing season months were the constant monthly values determined from the calibration and were very small.

The long-term monthly averages of Ep using the Penman equation generated from time series of meteorological data from 1950-1979 agreed well with the average of Class A pan evaporation measurements for Norfolk, Connecticut, and Lakeport, New Hampshire, as reported by Farnworth and Thompson (1982). As in the case of using pan values, the generated Ep values were multiplied by 0.70 to estimate reservoir evaporation.

POTENTIAL CLIMATE-CHANGE IMPACTS

Introduction

Because considerable uncertainty exists as to the exact meteorological impacts should the amount of CO_2 in the atmosphere double, the EPA requested that the project team run a set of possible scenarios. These include changes predicted by several general circulation models and separate arbitrary sensitivity analyses of precipitation and temperature.

General Circulation Models

GCMs are complex numerical models of atmospheric circulation that model variables such as winds, precipitation, temperature, radiation transfer, cloud cover, air pressure, and humidity. Because of their complexity, they use large-scale grid systems--a typical grid size is 4 degrees latitude by 8 degrees longitude. Within a grid, parameter values are averaged over the atmospheric, land, and sea conditions within the grid.

The advantage of using GCMs over sensitivity analysis of selected variables to study the possible impacts of climate change are their internal consistency and strong physical basis (McCabe and Ayers, 1989). The GCM results used in this project are from the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL, with Q-flux procedure). In the future, it is also planned to use the results of the Oregon State University (OSU) and United Kingdom Meteorological Office (UKMO) models. The models are summarized by Jenne (1989) and the outputs of the GCMs were supplied by the National Center for Atmospheric Research (NCAR).

The project team compared the climate determined by GCMs for present conditions (1 X CO_2) to actual measured data from the area and also reviewed Kalkstein's (1989) comparison study. None of the GCMs' current climates exactly represent the measured climate. In fact, for some models and parameters, the match is very poor. This, however, is not unexpected; the surface areas being modeled by a GCM are not exactly the same as the areas from which historical data were analyzed and only in the last few years has much effort gone into improving the hydrologic components of GCMs. It is positive, however, that the monthly changes in variables shown by the GCMs generally agree with historical data. In this study, GCM results were not considered predictors of future conditions; rather they were considered to be possible scenarios of the future.

Procedures

The procedures used for each scenario were generally similar. The EPA considers the period of 1950 to 1980 as representative of present climate conditions. Therefore, since the safe yield model requires streamflow, precipitation, and evaporation (Ep) time series, the objective was to determine how these time series might change under the various doubling of CO_2 (i.e., 2 X CO_2) scenarios and impact safe yield. Because of hydrologic data and safe yield model limitations, the actual period used in this study was October 1950 to September 1979.

The time series variables necessary to generate streamflow are precipitation and temperature and potential evapotranspiration (Et). As discussed earlier, both Et and Ep can be determined from incident solar radiation, temperature, wind speed, and relative humidity (which can be determined from GCM variables of air pressure, temperature, and specific humidity or mixing ratio). Therefore it must be determined how the driving variables may change under 2 X CO_2. Since the GCMs do not agree with present climate, but may be generally representative, it is reasonable to adjust the present measured values of the driving variables by the monthly ratio of the 2 X CO_2 scenario value to the 1 X CO_2 value. The one exception is temperature; there the present temperature is increased by the monthly absolute temperature change predicted by the GCM. These methods have been used in previous studies (for example, in those summarized by Smith and Tirpak (1989)).

GISS

Compared to the present climate, the GISS 2 X CO_2 climate will be warmer with slightly less precipitation, be slightly less windy, have slightly less relative humidity, and have higher solar radiation with less cloud cover. This resulted in an average increase in Et of 20 percent. The resultant changes in average monthly streamflow for the Ware River compared to the base case (representative of present climate) are shown in Figure 2. The impact in the Connecticut River is similar. The major cause of the average decrease in flow of 16 percent is the increase in Et. The peak occurs earlier than in the base case because snowmelt occurs sooner and the low-flow season has less flow and extends longer. The impact of these flow changes upon safe yield is a decrease in base-case yield of 306 mgd to 236 mgd (23 percent decrease). Besides lesser inflows to the reservoirs from tributary streams, the large decrease is also due to increased evaporation from the reservoir surfaces (an average increase of 17 percent), increased releases from Quabbin Reservoir due to lower flows in the Connecticut River at Montague, and less flood skimming from the Ware River. The results are summarized in Table 2.

GFDL

Compared to the GISS 2 X CO_2 climate, the GFDL 2 X CO_2 climate will be warmer and windier, will have less precipitation and somewhat less relative humidity, and will have more radiation with less cloud cover. These conditions result in the GFDL Et and Ep being significantly higher than those of the GISS scenario and present climate. Figure 2 shows the impacts on Ware River streamflow. As shown in Table 2, streamflows are 33 percent less than under present climate and the safe yield is decreased by 43 percent.

Table 2.

Summary of Results

Run	Et %	Ep %	Precip %	Temp Cel.	Flow %	Yield mgd
Base	-	-	-	-	-	306
GISS	+20	+17	-1.6	+3.67	-16	236
GFDL	+57	+41	-7.6	+4.9	-33	173
2,0%	+12	+6	0	+2	-8	278
2,+20%	+12	+6	+20	+2	+23	379
2,-20%	+12	+6	-20	+2	-39	161
4,0%	+24	+11	+0	+4	-15	250
4,+20	+24	+11	+20	+4	+15	355
4,-20%	+24	+11	-20	+4	-44	139
4,+10%	+24	+11	+10	+4	+0.2	302
4,-10%	+24	+11	-10	+4	-30	196
Incr. rc	+5	+17	-1.6	+3.76	-10	262
Ext. Sea.	NA	+17	-1.6	+3.67	NA	195

Note: Reported by percent of average change for Ware and Connecticut Rivers compared to base case except for temperature, which is increase in temperature (degrees Celsius) and yield, which is mgd. 2, +20% means 2 degree temperature increase and 20 percent increase in precipitation. "Incr. rc" is increasing value of rc due to CO_2 enrichment. "Ext. Sea" is increasing growing season.

Sensitivity to Temperature and Precipitation Changes

Another series of analyses examined the sensitivity of the streamflow and reservoir systems to combinations of changes in temperature and precipitation. The temperature increases ranged from 2 to 4 degrees (Celsius); precipitation changes ranged from none to increases and decreases of 10 and 20 percent. The results are summarized in Table 2. In the calculations of Et and Ep, only the temperature terms in the Penman-Monteith and Penman equations were changed. No changes were made in parameters that might be indirectly impacted by temperature change such as, for example, increases in rc (canopy resistance) as the soil dries.

As can be seen in Table 2, the worst case occurs if temperature increases 4 degrees and precipitation decreases 20 percent. If precipitation were to increase 10 to 20 percent, it would mitigate the impacts of a 2 to 4 degree temperature rise. In some cases, safe yield would actually increase. Unfortunately, many researchers (for example, Rind, 1991) and GCMs indicate that precipitation will remain the same or decrease in the northeastern United States. As the results in Table 2 show, if these occur, with or without accompanying changes in other climate features as shown by GCMs, the impacts on streamflow and safe yield will be severe.

Sensitivity to Canopy Resistance

Rosenberg et al. (1990) present a comprehensive discussion of the potential impact of vegetation growing in an enriched CO_2 environment. They suggest that under this scenario, the rc could increase by 22 percent because the decrease in transpiration due to stomatal narrowing would be greater than the increase in transpiration due to increased leaf areas. They also report that this is still an area of research and may not actually occur in fields and forests in 2 X CO_2 climates. The project examined the sensitivity of the water supply system to this possibility by increasing the monthly values of rc by 22 percent, and then determining the resulting Et, streamflow, and safe yield for the GISS scenario. As shown in Table 2, ET increased by only 5 percent (compared to 20 percent in the other GISS scenario), and streamflows and the safe yield were higher than in the first GISS scenario. Therefore, if rc did increase under enriched CO_2, some of the impacts of climate change might be mitigated. Ep, however, would still probably increase and cause increased reservoir losses.

Sensitivity of Length of Growing Season

While there were increases in Et during the growing season in each of the previous scenarios, there was no increase in the length of the growing season due to increased temperatures. In this scenario, it was assumed that the growing season would extend from March through November in both river basins instead of April through October in the Ware River basin and May through October in the upper Connecticut River basin. To model these impacts using the GISS scenario, the monthly Et values used in the runoff model corresponding to the extra growing season months (originally calibration parameters in the models) were increased by the ratio of the Et values for first GISS scenario to the base-case Et values. Compared to the first GISS scenario, this resulted in an increase in Et of 12 percent in the Ware basin and 5 percent in the Connecticut basin, a streamflow decrease of 14 percent in the Ware basin and 5 percent in the Connecticut basin, and a safe yield decrease of 17 percent from 236 mgd to 195 mgd. Therefore, if there are increases of a few months in the growing season, streamflows and safe yields will be decreased significantly.

Reliability of 306 Million Gallons Per Day

Under the base case (present climate), the reliability of the safe yield of 306 mgd is 98.5 percent (i.e., the monthly demands averaging 306 mgd annually can be fully supplied during 98.5 percent of the months simulated). The reliability of supplying 306 mgd under the first GISS scenario is 83.4 percent. If drought-management practices are simulated, the reliability increases to only 86 percent. As discussed in the previous description of the safe yield model, drought-management practices include decreasing demand during times of low reservoir storage. The impact of the lower reliability is that instead of only 4 months in 30 years when demand cannot be met under the base case (present climate), failures would occur in approximately 50 months under the GISS scenario.

Comparisons to Other Studies

The magnitudes of the decreases in streamflow are similar to those found in other studies. McCabe and Ayers (1989) found possible decreases in the flow of the Delaware River basin. For example, in their scenario of a 2 degree temperature increase and 20 percent precipitation decrease, they found a 51 percent flow decrease. This study of the MWRA showed a decrease of 39 percent. The impact of the GISS scenario for the Delaware River basin was a flow decrease of 25 to 39 percent. For the Ware and Connecticut basins, the flow decrease was 16 percent. Schaake (1990) calculated similar possible decreases of flows in the southeastern United States. Rosenberg et al. (1990) found that in a forest in Tennessee, there would be no change in Et under the GISS scenario if rc is increased due to CO_2 enrichment.

CONCLUSIONS

Even though this project has been as thorough as time and budget allowed in its investigation of the potential impacts of global climate change, it has some of the same limitations as similar studies:

- Uncertainty related to predictions by GCMs
- Disagreement among GCMs
- The methodology to apply the results of GCMs to river basin studies
- Uncertainty of the impacts of doubling CO_2 upon vegetation changes, transpiration characteristics, growing season, and albedo
- Assumptions in the Et, Ep, and runoff models that may be violated under climate change
- Possible changes in the operating policies of water resources systems in response to climate change
- Inconsistencies in doing sensitivity analysis on only precipitation and temperature when other important variables will also be affected by climate change

However, the study does have enough rigor (some examples are the strong verification of the Et, Ep, and runoff models and the logic of the results) to conclude that the impacts of possible climate change on Et, Ep, streamflow, and reservoir yield will be similar to the range of impacts shown in this study. These show serious decreases in streamflow and yield due to the prediction of GCMs, temperature changes alone, and increases in growing seasons. In addition, the peak flow occurs earlier than in the present climate because snowmelt occurs sooner and the low-flow season has less flow and extends longer. If precipitation is also decreased, the impacts are even more severe. Impacts are only mitigated if there are increases in precipitation (unlikely in the Northeast) or canopy resistance increases due to enriched CO_2 (which may or may not occur). The negative impacts in reservoir yield occur not only because there is less streamflow, but also because flow maintenance requirements result in less of the flows being available. Therefore, it appears that climate change could have significant detrimental impacts upon streamflows and reservoir yields in the Northeast.

Further work in this study will include applying the OSU and UKMO scenarios. An investigation is also needed on the impacts of climate change on water demand; demand on the MWRA system may increase because of more water use (for example, lawn watering) and less reliable local supplies. This investigation will be conducted in a later part of this study.

Once these possible supply and demand changes are known, the MWRA must decide how it will respond to this information. There seem to be at least several levels of responses. For example, the MWRA might alter its present short- and long-term planning methodologies. Another is what, if any actions, the MWRA will undertake now or in the future to attempt to mitigate or adapt to possible climate-change impacts. These issues will also be examined in a later phase of this study.

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THE WATER SUPPLY SYSTEM OF NEW YORK CITY AND GLOBAL CLIMATE CHANGE

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ABSTRACT

This paper describes the New York City water supply system, reviews some of the impacts of global environmental change (primarily global warming) on it, and suggests some planning guidelines. The assessment of the impacts of global environmental change on urban water systems is an emerging field; one of the few available reviews is Schwarz and Dillard (1990). This paper is designed as an initial assessment of the problem with respect to a single large regional urban water supply system. The paper has four parts: (1) a description of the system and water use in the system, (2) a summary of planning issues relating to the system, (3) a review of potential impacts from global environmental change, and (4) some planning guidelines.

THE NEW YORK CITY WATER SUPPLY SYSTEM

System Description

The New York City water supply system is shown in Figure 1; a concise yet comprehensive description of the system is essential for considering the impacts of global environmental change on it. Much of the material in this section is drawn from the second interim report of the Mayor's Intergovernmental Task Force on New York City Water Supply Needs (1987a) and a draft of the Task Force final report. The present writer was the principal editor of both reports.

In the system, water is collected from upland watersheds, held in storage reservoirs, and sent via a system of tunnels and aqueducts through balancing and distribution reservoirs to distribution mains in the city and other user areas. The system operates almost entirely by gravity (the highest reservoir, Neversink in the Delaware system, has its spillway at 1,440 feet above mean sea level). About 97 percent of the total water supply is delivered to the distribution system by gravity; only 3 percent is electrically pumped to maintain desired delivery pressures. The system is thus an economical one, with operating costs relatively insensitive to changes in energy prices.

Water is collected and stored in three upland reservoir systems: Croton, which began service in 1842 and was completed as a system prior to World War I; Catskill, completed in 1927; and Delaware, completed in 1967. The total area of the watersheds is nearly 2,000 square miles. The three systems meet respectively about 10, 40, and 50 percent of the total daily system demand. The systems deliver water to the city via the New Croton Aqueduct, the Catskill Aqueduct, and the Delaware Aqueduct. The New Croton Aqueduct delivers water from the Croton system to the Jerome Park Reservoir in the Bronx and thence to the Central Park Reservoir in Manhattan. Catskill and Delaware water flows via Kensico Reservoir to Hillview Reservoir, just north of the city line. From there city Tunnels #1 and #2 deliver it to the city distribution system, which includes some 6,000 miles of mains varying in size from 6 to 96 inches in diameter. City Tunnel #3 is now under construction; when completed through its second stage it will provide not only additional capacity but also the opportunity to shut down City Tunnels #1 and #2 for inspection and rehabilitation. The 18 impounding reservoirs, three controlled lakes, aqueducts, tunnels,

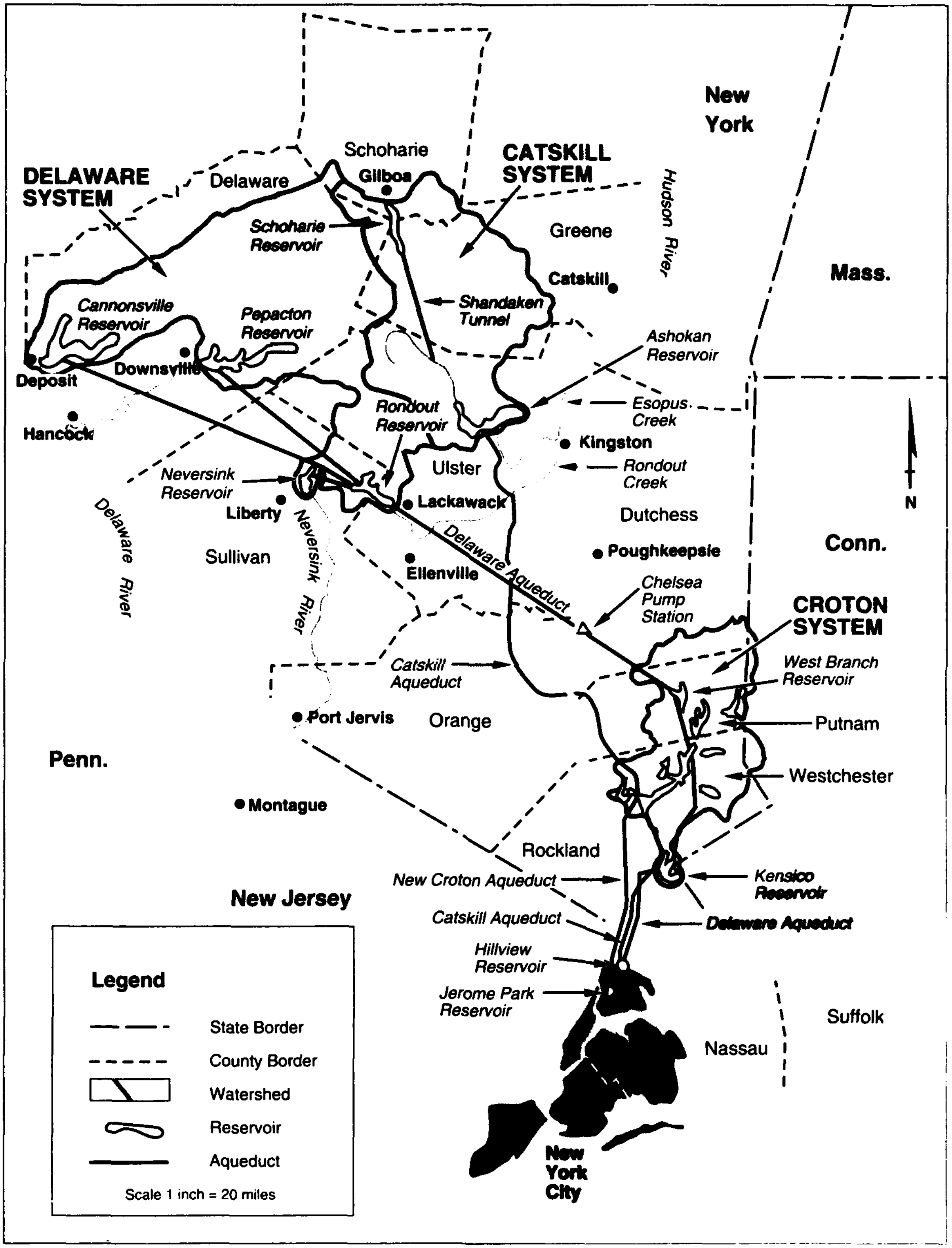

Figure 1. **Watersheds, reservoirs, and aqueducts of the system.**

and water mains that make up the city water supply and water distribution systems together constitute a monumental hydraulic and civil engineering achievement. A detailed description of the system can be found in the Official Statement documents issued in connection with proposed bond sales. (A recent example is New York City Municipal Water Finance Authority, 1989.)

The total storage capacity of the system is 547.5 billion gallons. The safe yield is currently estimated by standard hydrologic methods to be 1,290 million gallons per day (mgd), with 240, 470, 480, and 100 mgd available from the Croton, Catskill, Delaware, and Rondout watersheds, respectively. (Rondout watershed is in the Hudson River basin but is operationally part of the Delaware system.) Safe yield is defined as the amount of water that could be supplied on a continuous basis by the system should there be a recurrence of the worst drought of record (in the mid-1960s). System safe yield could be lower than that currently calculated as a result of future droughts and changes in the city's releases to meet U.S. Supreme Court and New York State requirements.

A factor that constrains the availability of water from the watersheds, in addition to the basic yield limit, is the delivery capability of the aqueducts. For example, maximum transmission capability of the system above Kensico Reservoir, including the New Croton Aqueduct, is estimated as 1,720 mgd (Mayor's Intergovernmental Task Force on New York City Water Supply Needs, 1987b, p. 88). Average daily demand in the summer period is about 1.1 times average annual daily demand. Therefore any future average annual daily demand south of Kensico greater than 1,564 mgd (1,564 X 1.1 = 1,720) would result in the system's delivery capability above Kensico being exceeded during the summer even with full pumping of Croton system water, which in turn would result in the depletion of storage at Kensico Reservoir.

An important set of restrictions on the operation of the system is the Supreme Court decree of 1954, as supplemented by the Good Faith Agreement of 1982 (Parties to the U.S. Supreme Court Decree of 1954, 1982). The decree and the agreement specify limits on city diversions from the Delaware River basin, and prescribe certain releases from the city's Delaware River basin reservoirs to prevent saltwater intrusion and for other purposes in the lower Delaware River. These releases are related to flows measured at Montague (Figure 1) and Trenton, New Jersey. In addition, an agreement between the city and the New York State Department of Environmental Conservation made in 1980 provides that the city will supply augmented conservation releases during normal conditions from its Delaware basin reservoirs, and conservation releases from Rondout Reservoir and the Croton system.

Water Supply

Water from the system is used to supply all of New York City, including the service area of the investor-owned Jamaica Water Supply Company in Queens, which currently receives 30 mgd of city system water. In addition, the city system supplies 85 percent of the water used in Westchester County and 5 to 10 percent of the water used in Orange, Putnam, and Ulster counties. Areas using system water are shown in Figure 2. There are also upstate communities that do not regularly use water from the city system but are connected to it for emergency use. Upstate municipal corporations and water districts in counties (except Dutchess) in which the city has water supply facilities have certain legal entitlements to provide connections to the system and to take water, at a price set by the State Department of Environmental Conservation, in quantities no greater than their populations times the city's per capita use. The price set by the state for this water is limited by provisions in Section C of the Water Supply Act of 1905, and may not exceed the price charged for water within the city.

The average daily system demand in 1988 was 1,581.7 mgd, of which 1,456.5 mgd went to the city (including 26.3 mgd to the Jamaica Water Supply Company) and 125.2 mgd to other consumers. This total exceeded the previous system high average daily use of 1,557 mgd in 1979; however, use within New York City excluding the Jamaica Water Supply Company area was below the figure for 1979. While the percentage of the 1988 water

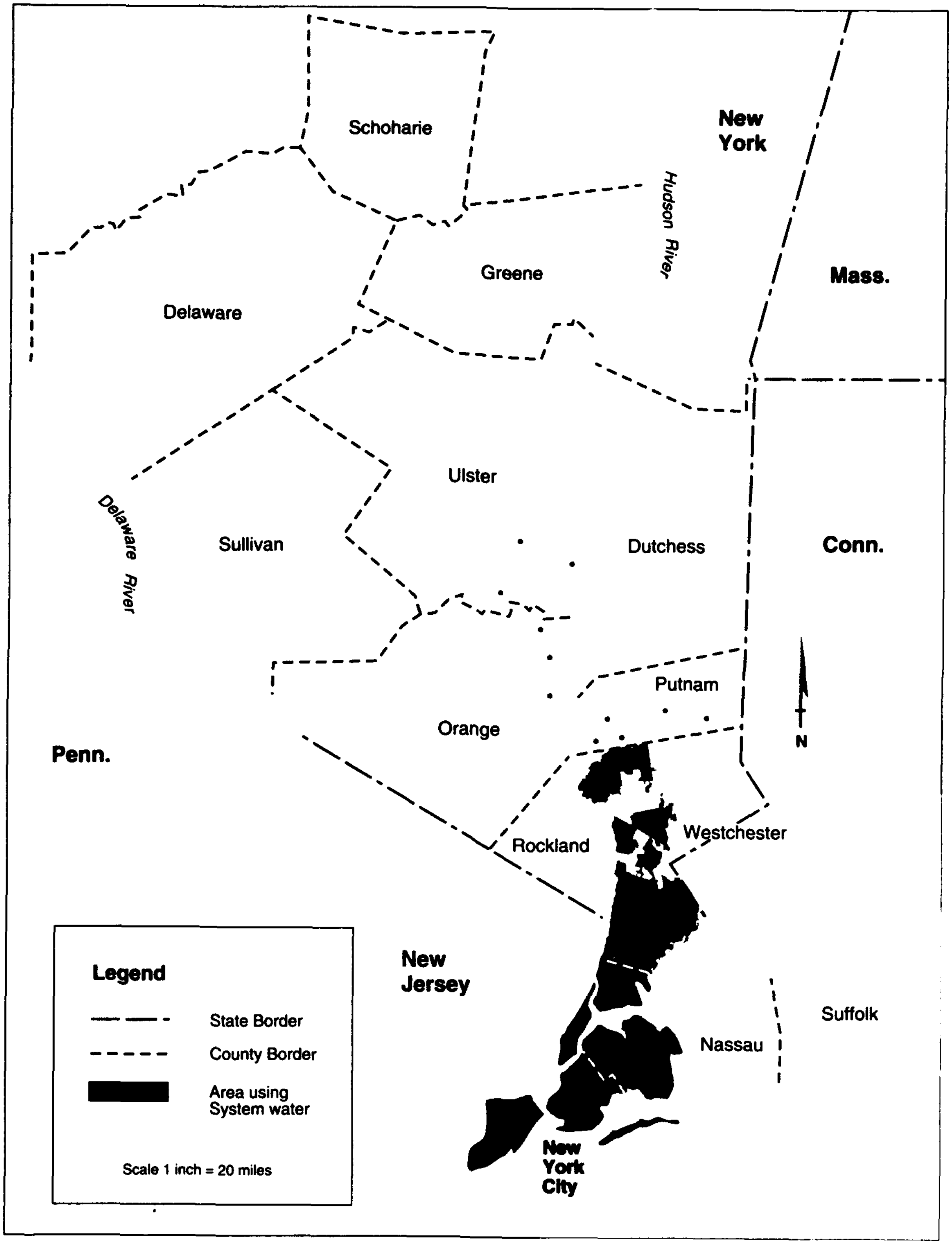

Figure 2. **Areas using New York City system water.**

supply total going to other users, 8 percent, may not seem large, the size of the system is such that this amount is sufficient to supply the entire combined needs of the cities of Albany, Rochester, and Syracuse.

The Water Budget

Mean precipitation on the city's watersheds for the 52 years of record from water year 1938-1939 to water year 1989-1990 was 44.65 inches. During this period, maximum yearly precipitation was 55.67 inches in the 1977-1978 water year, and the minimum precipitation was 27.97 inches in the 1964-1965 water year (during the drought of record). The maximum precipitation was thus almost exactly twice the minimum. This precipitation provides the runoff that generates yield to the system. The yield in turn depends on a variety of factors, including the natural and human-influenced characteristics of the watersheds and the distribution in time of the precipitation that occurs in a given year.

The annual demands on system yield are, in order of magnitude, demands from New York City, augmentation and conservation releases, and upstate demands. This can be illustrated with the figures from the 1988-1989 water year, expressed as volumes rather than as mgd. In 1988-1989, total demand for the entire system was 660.5 billion gallons. Of this, 513.5 billion gallons were delivered to New York City for water supply; 82.5 billion gallons were released to augment flow in the Delaware River; 19.8 billion gallons were used for New York State conservation releases; and 44.7 billion gallons were delivered to outside communities for water supply. The percentages of use for water year 1988-1989 were 78 percent for the New York City water supply, 15 percent for the two categories of releases, and 7 percent for outside community water supply.

Water Quality

The water quality of the system is exceptionally high, and the only treatment procedures routinely used to maintain quality are detention, screening, addition of caustic soda for pH control, and chlorination for disinfection. Fluoridation is also used, and alum is applied in the Catskill Aqueduct to control turbidity when necessary. In the near future, corrosion inhibitors will be added to control corrosivity in the water. There are five laboratories that monitor water quality in the system; about 80,000 samples a year are collected, and approximately 1 million analyses made. Routine checks are made for some 60 substances. There are watershed inspectors who maintain surveillance of the watersheds and city-owned and -operated upstate sewage treatment plants to prevent the discharge of untreated sewage into watersheds.

Continuing development in the Croton watershed has resulted in pressure on water quality there. To deal with this and to meet more stringent regulatory standards, a full-scale water-filtration plant at Jerome Park Reservoir is currently being planned. The total cost of this program is estimated to be $670 million. Under the 1986 Safe Drinking Water Act Amendments, the U.S. Environmental Protection Agency has issued, among other water quality rules, criteria for surface-water treatment and filtration that can be expected to have substantial cost implications for the city system.

In a major new initiative in water quality protection, the city in September 1990 issued a discussion draft of proposed regulations for the protection from contamination, degradation, and pollution of the New York City system (New York City Department of Environmental Protection, 1990). The issuance of this discussion draft began an extensive public involvement process that is intended to lead to regulations that will ensure the maintenance and improvement of the city system's water quality through the implementation of appropriate watershed management practices.

System Simulation Models

The city uses three hydrologic simulation models to analyze the whole system and specified portions of it. The principal model used to evaluate and manage system operations is the Reservoir Systems Analysis simulation model (RSA model). A version of this model, based on a model originally developed by the New York State Department of Environmental Conservation, is described in Laedlein and Mayer (1985). The RSA model is a monthly simulation model designed to analyze the total New York City water supply system on an integrated operation basis. The model can be used to examine (1) the water supply capability of the system under various release and diversion schedules, (2) the impact of operating rules on system capabilities, and (3) the impact of physical system changes. As is typical in simulation models, the system is represented in the RSA model as a series of connecting nodes. The program is coded in FORTRAN and is operated on the city's mainframe computers. This model has been maintained for a substantial time by the city, and is modified as required to take into account structural changes and changes in operating procedures.

In addition to the RSA model, the city maintains its Daily Simulation Model of the Delaware system for the purpose of evaluating specific system functions, in particular the impacts of conservation release requirements on hydroelectric operations. The third simulation model used by the city is the Delaware River Basin Commission's Daily Flow Reservoir Operation Model, developed originally for the U.S. Army Corps of Engineers (1980). This model is used to evaluate the effects of proposed operation policies and projects on the Delaware River. It has recently been extended to encompass a 60-year flow regime (from 50 years), and additional sites have been added for flow analyses below the Neversink and Pepacton reservoirs (Delaware River Basin Commission, 1990, p. 37).

Drought Management

The city maintains a Drought Management Plan to control water use and supplement water supply during periods of drought. The plan has three phases, invoked sequentially as a drought becomes more serious. The three phases are Drought Watch, Drought Warning, and Drought Emergency. The last includes four stages with increasingly severe mandated use restrictions. (The 1985 and 1989 droughts brought the system to the third of these four stages.) In addition, the city has an emergency water supply available from the Chelsea Pumping Station, located on the east bank of the Hudson River in Dutchess County. This station can pump up to 100 mgd from the Hudson River into the Delaware Aqueduct. It was used in the summer and fall of 1985 and for 2 weeks in May 1989, under emergency approval from the New York State Department of Health. In 1986 the city applied for an operating permit from the State Department of Environmental Conservation. In May 1990 this application was modified by the city; a revised application is being submitted with a new draft environmental impact statement.

PLANNING ISSUES

The most important planning work for the system has been done in recent years by the Mayor's Intergovernmental Task Force on New York City Water Supply Needs. The work of this exceptionally effective voluntary regional group will be described in the writer's book in progress on the New York City water supply system. The Task Force was formed in 1985 during the drought of that year to assess the city's long-range water supply needs and the adequacy of planning efforts to meet those needs. The Task Force, composed of federal, state, and local government officials who oversee various aspects of local and/or regional water supply management and development, was asked to recommend long-term priorities for the city and actions to ensure that these priorities would be achieved. The first interim report of the Task Force was *Increasing Supply, Controlling Demand* (1986), and the second interim report was *Managing for the Present, Planning for the Future* (1987a, with an appendix volume containing committee reports, 1987b). A related planning effort is the New York State Water Resources Management Strategy for the Delaware-Lower Hudson Region (New York State Water Resources Planning Council, 1989). This includes both assessments and strategies for the Delaware-Lower Hudson and adjacent planning areas that together embrace all of the city's watersheds and service areas.

The Task Force, through its committees, undertook a comprehensive examination of planning for the New York City system. It supported and guided the city's Universal Metering Program, now in progress; the development of a demand forecasting system, which is currently being further developed; and other key conservation and planning measures. The demand model (New York State Department of Environmental Conservation and New York City Department of Environmental Protection, 1989) is based on techniques developed in Howe (1982), Howe and Linaweaver (1967), and Davis et al. (1988); a critique is in New York State Water Resources Institute (1990). In broad overview, the Task Force has found that because usage is consistently higher than safe yield for the system, two courses of action are prudent. First, all reasonable demand-management and conservation measures should be implemented; and second, planning for new supplies should begin in a consistent and orderly way now in the event that these are required in the future. The safe yield criterion is not the most sophisticated criterion of system planning, but this two-pronged approach appears to be appropriate for the New York City system even with fine-tuning of the decision criterion.

Factors that might increase total demands on the system (in addition to global warming impacts considered below) include demand growth in existing use areas, the addition of new user communities both up state and on Long Island, and additional conservation demands by the state. Further, a new drought of record would decrease the safe yield estimate. Conservation measures will offset demand growth to an extent that is presently unknown; the most important of these measures are the Universal Metering Program and the associated move from flat-rate pricing to metered per-unit pricing. Under the metering program, all connections in the city will be metered by the late 1990s. About half of all connections are now metered; about 23 percent, mostly industrial and commercial connections, were metered prior to the start of the program. Other important conservation programs include the city's low-flow fixtures law and possible retrofit programs. Among potential supply alternatives are an increase in the capacity of the Chelsea pumping station, larger withdrawals from farther up the Hudson, and the use of the *Brooklyn/Queens aquifer (New York City Department of Envirohmental Protection,* 1987).

These planning issues are well described in the reports of the Mayor's Task Force. On the institutional side, in order to continue the cooperative regional planning efforts embodied in the work of the Mayor's Task Force, a successor organization has been founded, the Southeast New York Intergovernmental Water Supply Advisory Council.

POTENTIAL IMPACTS OF GLOBAL WARMING

The Task Force has noted the need to be aware of climate-change impacts on the system (Mayor's Intergovernmental Task Force on New York City Water Supply Needs, 1987a, p. 17), although there has not been as yet an extensive effort to consider these in any systematic way. On the other hand, the system does have one of the few concrete adaptations to global warming in any large water supply system, an outflow pipe for the Third City Tunnel on Roosevelt Island built higher than originally planned explicitly to take into account the possibility of rising sea levels (Hurwitz, 1987). (The redesign was not total; however, the designers raised the outlet to the extent possible within existing design constraints, rather than redesigning completely.) This example is mentioned in Schwarz and Dillard (1990, p. 348).

It is now generally assumed that global warming is likely, and that it will be accompanied by a significant rise in sea levels. On the other hand, it is accepted that current global-climate-change models cannot forecast rainfall patterns with sufficient accuracy to indicate what will happen to precipitation in the New York City system watersheds. (An excellent overview of global warming is in Schneider, 1989. For an assessment of impacts, see National Academy of Science, forthcoming; and Ausubel, 1991.) Thus, planning becomes a matter of considering what elements of the system might be affected by global warming, what information will be needed to make decisions, and what the timing of such decisions should be. It should also be noted that there are some possible global or regional environmental changes other than or in addition to global warming that could have profound impacts on the New York City system, so that planning for global warming is only a part, albeit an important part, of planning for environmental change.

There are potential impacts of global warming both on demand and on supply in the New York City system. Demand could increase because of increased air-conditioning and other demands associated with warmer weather. (If precipitation were to increase in the region, on the other hand, outdoor sprinkling demands might be reduced.) The largest potential increases in demand on the system, however, would probably result from supply problems in neighboring regions. If there were substantial saltwater intrusion into the Long Island aquifers because of rising sea levels, a very substantial additional demand could fall on the New York City system from Nassau and Suffolk counties. Whether this could reasonably be met will depend in part on whether the fourth stage of City Tunnel #3, which goes to eastern Queens, is designed to a sufficiently large scale. Saltwater intrusion into the Delaware could result in reopening decisions based on Supreme Court rulings, and could place substantial additional demands for releases on the New York City system. Further, New York State could require larger conservation releases within the system.

On the supply side, saltwater intrusion could remove the Brooklyn/Queens aquifer as a supply source. Sea-level rise and the concomitant increased saltwater intrusion in the Hudson could remove the Chelsea pumping station as an emergency source and also prevent its expansion as a supplemental source, requiring any new source to be farther up the Hudson. (This would potentially also require Poughkeepsie, which takes its water directly from the Hudson, to seek other sources, perhaps adding this city to the list of New York City system users.) If rainfall decreases in the watersheds as a result of global warming, this would put further pressure on the city to develop new sources; increased rainfall would offset some of the demand problems foreseen from global warming. Overall, unless offset by substantially increased rainfall in the watershed areas and/or highly effective new technologies for conservation, the impact of global warming on the New York City system may be to tip the balance toward the need for new sources.

PLANNING GUIDELINES

Given the nature of the New York City water system and the possible impacts of global warming, what are reasonable planning guidelines for the city, regional, and state planners who deal with the system? At least six can be suggested:

1. The potential impacts of global warming increase the importance of devoting substantial resources to planning for the New York City system, including the development of additional models. This writer's impression is that for many years, since the early 1970s, the United States has devoted far too little to water resources planning, and this urgently needs to be remedied. Certainly New York City has been fortunate to have an effective volunteer group lead planning for the system. However, as detailed planning efforts get under way, the city itself needs to devote additional resources to this function over the long term. (For related comments, see Major and Schwarz, 1990, pp. 167-168.)

2. Global warming will increase the complexity of planning, and in response planners will have to continually improve their planning and decision criteria. A commendable current example of such improvement is in the city's Request for Proposals for studies of potential Hudson River projects (New York City Department of Environmental Protection, 1989). This document includes the requirement that optimal scheduling of projects be studied with mathematical modeling techniques at least at the level of sophistication of mixed integer programming.

3. The city system planners need to track the progress of global warming and its impacts as a regular part of their work. In this respect, the city system's planners need to be plugged into international science in the same way they were once, in the palmy days of system development, plugged into international engineering.

4. The system planners also need to track what will become a large body of knowledge on the human dimensions of global environmental change. One can refer here, by way of example, to the work of the committee for Research on Global Environmental Change of the Social Science Research Council. One of this committee's projects is a multi-national study of social learning in the presence of environmental change: how societies learn about recognizing and adapting to environmental problems, including global warming.

5. All of the city's many planning contracts relating to the water system should include a provision requiring the careful examination of the effects of potential global warming impacts on system design.

6. Last but not least, the example of the designers of the Roosevelt Island outflow pipe should be followed and expanded to include more complete redesign than was possible in that case. There will be other, and perhaps many, elements of the water system that can be adapted simply and at relatively low cost to global warming and sea-level rise. Planners should be looking for these elements during all of their work with the system.

In summary, it appears that there may be substantial impacts of global warming on the New York City water supply system. Barring "the non-negligible probability that climatic change will follow a catastrophic course," (Ausubel, 1991, p. 213) these impacts should be within a range that, while serious and important, can be dealt with effectively by devoting increased planning and material resources to them. These resources need to be brought to bear in the reasonably near future. Planners must make this necessity clear to decision-makers.

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EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES IN THE DELAWARE RIVER BASIN

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ABSTRACT

The U.S. Geological Survey in 1988 began a study of the effects of climate change on water resources in the Delaware River basin. As part of this study, a hydrologic model of the basin was developed that included the operation of water diversions and reservoirs. The hydrologic model was used to examine the sensitivity of water resources in the basin to prescribed changes in temperature, precipitation, and the stomatal resistance of plants to transpiration.

Results of simulations made using the model indicated that within the ranges of the prescribed changes in mean annual precipitation (-20% to +20%) and temperature (0 to +4°C), drought frequency (as defined by streamflow and reservoir contents) was more sensitive to changes in precipitation than to changes in temperature. In contrast, irrigation demand was more sensitive to changes in temperature than to changes in precipitation. The results also indicated that all water resources components of the basin could be very sensitive to prescribed changes in the stomatal resistance of plants to transpiration.

The predicted effects of natural climate variability were as large as the modeled effects of the prescribed changes. Because natural climate variability causes such large changes in basin water resources, it can mask the effects of long-term climate trends.

INTRODUCTION

Scientists have predicted that increasing concentrations of atmospheric carbon dioxide (CO_2) may cause global warming and changes in temporal and spatial patterns of precipitation (Bolin, 1986; Schlesinger, 1988). Some research also has shown that the stomatal resistance of plants to transpiration is increased in a CO_2-enriched atmosphere, thereby decreasing transpiration rates (Idso and Brazel, 1984). Such changes in temperature, precipitation, and plant transpiration may have important effects on water resources. In 1988, the U.S. Geological Survey began an interdisciplinary study of the sensitivity of water resources in the Delaware River basin to climate change (Ayers and Leavesley, 1988). This paper summarizes results for several components of the study.

The Delaware River Basin

The Delaware River region, which lies along the East Coast of the United States, encompasses about 30,000 km^2 (see Figure 1). The basin has a humid, temperate climate with a mean annual temperature of about 12°C and mean annual precipitation near 1,200 mm. Soils and topography vary considerably within the basin. Soils range from thick, sandy-loam soils to thin clay soils, and topography varies from low relief in the coastal areas to moderate relief in the northern part of the basin.

The Delaware River basin provides water for an estimated 20 million people within and outside the basin (Albert, 1987). Water availability is enhanced by a system of reservoirs, wells, and diversions. Two large diversions out of the basin are through the New York City aqueduct system and the Delaware and Raritan Canal (D&R Canal) (Figure 1). Releases of water from the reservoirs are managed to maintain specified minimum flows at Trenton, New Jersey. The minimum flows keep saline water down stream of important fresh-water supplies at Philadelphia, Pennsylvania.

The objective of the Delaware River basin study was to examine the sensitivity of the water resources in the Delaware River basin to climate change under existing water management policy and infrastructure. Certain aspects of the basin's water resources were of particular concern: (1) changes in streamflow, (2) changes in water storage in the New York City and other basin reservoir systems, (3) maintenance of prescribed minimum streamflow requirements, and (4) changes in irrigation demand.

HYDROLOGIC MODEL OF THE DELAWARE RIVER BASIN

To examine the sensitivity of the water resources in the Delaware River basin to climate change, a hydrologic model of the basin was developed that included the existing management policy and infrastructure. The model was based on a monthly time step water balance within the basin. The model was a modification of the Thornthwaite water balance, which is a water budget bookkeeping procedure that accounts for soil moisture, evapotranspiration, water deficit, snowmelt, and surface runoff (Thornthwaite and Mather, 1955; Tasker, 1990).

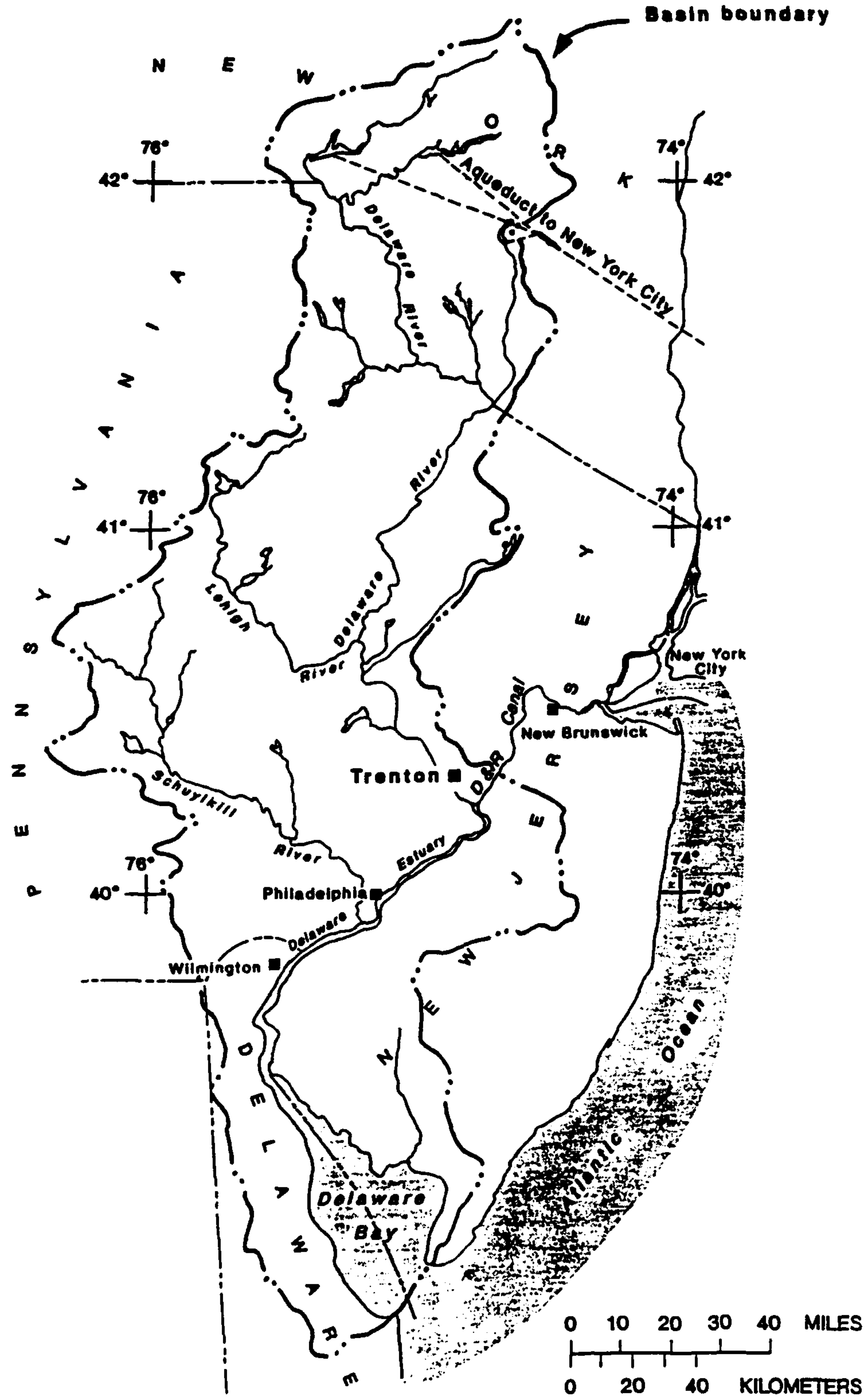
The water balance component of the model predicts unregulated streamflows based on climate inputs (monthly mean temperature and monthly precipitation) and a few simple parameters such as soil field capacity. (See McCabe and Ayers (1989) for a detailed description of the water balance component.) Because some studies have suggested that stomatal resistance of plants to transpiration increases as atmospheric CO_2 concentrations increase (Idso and Brazel, 1984; Rosenberg et al., 1990), a conceptual stomatal resistance factor (Wolock and Hornberger, 1991) was included in the water balance model.

Unregulated streamflow predictions are made at several key locations in the basin, such as the sites of reservoirs where critical management decisions are made. Basin operation rules then were applied at these key nodes. Reservoir storage, regulated streamflow, and the position of the salt front in the Delaware Estuary then were predicted for every time step in the simulation. The length of time that the basin was in a state of drought for a given simulation is computed as the number of months when the simulated reservoir storage or regulated streamflow drops below some specified level.

The water balance component of the model also was adapted to predict annual irrigation demand as a function of temperature, precipitation, and soil characteristics. Irrigation applications were based on the soil-moisture content predicted by the model.

SCENARIOS OF CLIMATE CHANGE

General circulation models (GCMs) of the atmosphere are often used to predict the effect of increasing atmospheric CO_2 on climate. There is an inherent scale problem, however, in interpolating predictions from GCMs to areas the size of the Delaware River basin. GCM nodes are spaced on a grid about 4° of latitude by 5° of longitude. The size of the Delaware River basin measures only about 3° of latitude by 1° of longitude. Thus, the basin is smaller than the distance between GCM nodes, and any prediction for small basins derived from such spatially coarse models should be questioned.



Base from Delaware River Basin Commission, 1986

Figure 1. **Map of the Delaware River basin.**

In an attempt to overcome the spatial incompatibility between GCMs and the Delaware River basin, surface weather patterns simulated by GCMs, such as frontal passages and high-pressure systems, were compared to observed weather patterns over the basin. It was reasoned that the spatial size of weather patterns (about 10° of latitude by 10° of longitude) was large enough to be reasonably predicted by GCMs and that knowledge of weather-pattern frequencies and characteristics in and around the Delaware River basin would provide adequate information for predicting temperature and precipitation.

GCM predictions of weather patterns (for both current and doubled-CO_2 conditions) were analyzed and compared to observed weather patterns. (See Hay et al. (in press) for a detailed description of GCM weather-pattern analysis.) Although GCM-simulated weather-pattern frequencies for current conditions matched well with observed weather-pattern frequencies, the weather-pattern frequencies predicted for doubled-CO_2 conditions matched observed data equally well. It was hoped that the GCMS would indicate that changes in weather-pattern frequencies from current to doubled-CO_2 conditions would be the primary driving force for changes in temperature and precipitation. This would have provided a scale-appropriate means of predicting future temperature and precipitation without relying on GCM predictions of changes in precipitation and temperature. The GCM results indicated, however, little or no changes in weather-pattern frequencies from current to doubled-CO_2 conditions.

Given the inability to use weather patterns to generate appropriate climate-change scenarios for doubled-CO_2 conditions and the lack of confidence in using GCM predictions directly, prescribed changes in precipitation and temperature were used in the analyses presented in this paper. The range in prescribed changes represented the range of GCM predictions of precipitation and temperature changes reported in the literature (Schneider et al., 1990). Also, because of the speculation that increasing concentrations of CO_2 may increase the stomatal resistance of plants to transpiration, prescribed changes in a conceptual stomatal-resistance factor (Wolock and Hornberger, 1991) were included in the climate-change scenarios. The range in prescribed changes in stomatal resistance reflects the range reported in the literature for doubled-CO_2 conditions (Rosenberg et al., 1990).

The prescribed temperature and precipitation changes were used with simple stochastic equations (Tasker, 1990) to generate multiple time series of temperature and precipitation that were subsequently input to the Delaware River basin hydrologic model. The stochastic equations permitted the study of the effects of long-term transient changes in climate on water resources, as well as the effects of steady-state changes. (For long-term transient changes, 100-year simulations were used; 30-year simulations were adequate for steady-state changes.) The stochastic equations also permitted the evaluation of the effects of prescribed changes in temperature and precipitation on water resources amid natural climate variability. Even with prescribed long-term changes in precipitation and temperature, natural climate variability creates a wide range of climate conditions that may occur.

RESULTS OF MODEL SENSITIVITY ANALYSES

Effects of Changes in Temperature and Precipitation

Streamflow and drought conditions (defined by streamflow or reservoir storage) were sensitive to the prescribed changes in precipitation and temperature. For example, the median drought frequencies derived from fifty 30-year simulations for various climate changes are given in Table 1. Drought frequency is the percentage of months during a 30-year simulation that the basin experienced drought conditions based on the contents of the New York City reservoirs. Drought occurred approximately 6 percent of the time for current climate conditions, but increased to 13 percent of the time for a warming of 2°C with no change in precipitation and increased to 29 percent of the time for a warming of 4°C with no change in precipitation. For the 2°C warming scenario, drought frequency increased to 90 percent for a 20 percent decrease in precipitation, but decreased to 0 percent for a 20 percent increase in precipitation.

Table 1. Median drought frequencies[1] in the Delaware River basin calculated from fifty 30-year simulations for various prescribed changes in temperature and precipitation.

Temperature Change[2]	Precipitation Change[2] -20%	-10%	0%	+10%	+20%
	Median Drought Frequency (%)				
0°C	79	29	6	1	0
2°C warming	90	50	13	3	0
4°C warming	96	70	29	7	1

[1] Defined here as the percentage of months during a 30-year simulation that the basin is in drought conditions based on contents of New York City reservoirs.
[2] Change from current mean annual temperature and precipitation (*1895-1988*).

Within the ranges of precipitation and temperature change used in this study, drought frequencies were more sensitive to precipitation changes than to changes in temperature (Table 1). Assuming a 2°C temperature increase, drought frequencies varied from 0 to 90 percent, depending on the assumed change in precipitation. In contrast, assuming a 10 percent decrease in precipitation, drought frequencies ranged from 29 to 70 percent, depending on the prescribed temperature change. The sensitivity of drought to precipitation coupled with uncertain GCM precipitation predictions for a CO_2-enriched atmosphere made the prediction of CO_2 effects on drought difficult.

Irrigation demand predicted by the hydrologic model also was sensitive to the prescribed changes in temperature and precipitation (Table 2) based on fifty 100-year simulations. The predicted annual irrigation demand was 174 mm for current climate conditions, 236 mm for a warming of 2°C with no change in precipitation, and 309 mm for a warming of 4°C with no change in precipitation. Annual irrigation demand was 278 mm for a 2°C warming combined with a 20 percent decrease in precipitation, and 201 mm for a 2°C warming combined with a 20 percent increase in precipitation.

Within the prescribed ranges of precipitation and temperature change, irrigation demands were more sensitive to temperature changes than to changes in precipitation (Table 2). For example, assuming a 2°C temperature increase, annual irrigation demand varied from 201 to 278 mm, a range of 77 mm depending on the change in precipitation. In contrast, assuming no change in precipitation, irrigation demand varied from 174 to 309 mm, a range of 135 mm depending on the prescribed temperature change. Temperature has a strong effect on soil moisture and irrigation demand through potential evapotranspiration.

Table 2. Annual irrigation demand for various prescribed changes in temperature and precipitation based on fifty 100-year simulations.

	Precipitation Change[1]				
Temperature Change[1]	-20%	-10%	0%	+10%	+20%
	Annual Irrigation Demand (mm)				
0°C warming	212	192	174	158	145
2°C warming	278	256	236	217	201
4°C warming	357	331	309	289	269

[1] Change from current mean annual temperature and precipitation (1895-1988).

Sensitivity analyses also indicated that increases in temperature can affect the timing of streamflow in areas where winter snow accumulation and spring snowmelt are currently important components of the annual water budget. Increased temperatures caused a greater proportion of winter precipitation to fall as rain and allowed more of the available precipitation to run off during the winter, thereby reducing the snow accumulation and the snowmelt runoff during spring.

The various water resources components of the Delaware River basin differed in their degree of sensitivity to climate change due, in part, to the current management policies practiced in the basin. Median drought frequency as defined by the contents of the New York City reservoirs was more sensitive to changes in precipitation and temperature than was median drought frequency as defined by streamflow at Trenton, New Jersey (Table 3). This difference in sensitivity resulted because the New York City reservoirs are the primary mechanism used to maintain minimum flows in the Delaware River. Storage in the reservoir system acts as a buffer to changes in unregulated streamflow caused by changes in temperature and precipitation.

Effects of Changes in Stomatal Resistance

The results of the sensitivity analyses performed in this study indicated that the water resources of the Delaware River basin were very sensitive to changes in stomatal resistance and that changes in stomatal resistance could offset the effects of increases in temperature and decreases in precipitation (Table 4). With a 2°C increase in temperature and no change in precipitation, annual irrigation demand was 240 mm, an increase of 60 mm over current irrigation demand (180 mm). With increases in stomatal resistance of 20 and 40 percent, however, annual irrigation demands were 132 and 54 mm, respectively; decreases of 48 and 126 mm from the current demand (180 mm). The reduction in transpiration caused by increased stomatal resistance more than offset the increase in potential evapotranspiration resulting from increased temperature.

Table 3. Effects of prescribed changes in temperature and precipitation on changes in median drought frequency based on fifty 30-year simulations.

Change in temperature	No change	+4°C	+4°C
Change in precipitation	No change	No change	-10%
Percentage of time in drought (based on streamflow at Trenton, N.J.)	3	9	20
Percentage of time in drought (based on contents of New York City reservoirs)	8	30	73

Table 4. Effects of prescribed changes in stomatal resistance in annual irrigation demand based on fifty 100-year simulations.

Change in Stomatal Resistance (%)	Annual Irrigation Demand (mm)
No change	240
+20	132
+40	54

Note: This scenario included no change in precipitation and a +2°C change in temperature. Predicted annual irrigation demand for current climate conditions was 180 mm.

Effects of Natural Climate Variability

Natural climate variability was a major factor affecting the prediction of the effects of climate change on water resources in the Delaware River basin. For a given expected future climate, natural variability created a wide range of climate conditions that may occur. The range in climate conditions that may be realized due to natural variability can mask the effects of changes in temperature and precipitation due to human factors. Table 5 gives a range of drought frequencies due to natural climate variability for several climate-change scenarios. Each scenario had a suite of possible drought frequencies; for instance, drought frequency ranged from 1 to 20 percent for current climate conditions and from 4 to 36 percent for a 4°C increase in temperature and no change in precipitation. The overlap in these distributions implies that natural climate variability can mask the effects of predicted long-term

Table 5. Range of distribution of drought frequencies[1] derived from fifty 100-year simulations of current climate conditions and several prescribed changes in precipitation and temperature.[2]

Climate Scenario	Drought Frequency (%)						
	0	10	20	30	40	50	60
Current Climate	<--------------->						
T+4°C	<--------------------->						
T+4°C, P-10%		<---------------------------------->					
T+4°C, P+10%	<--------------->						
P-10%	<--------------------->						

T = current mean annual temperature; P = current mean annual precipitation.

[1] Defined here as the percentage of months during a 100-year simulation that the basin is in drought conditions based on contents of New York City reservoirs.

[2] Change from current mean annual temperature and precipitation (1895-1988).

climate changes. Even if accurate predictions of long-term changes in mean temperature and precipitation can be made, a wide range of drought frequencies is possible because of unpredictable short-term variability in precipitation and temperature.

CONCLUSIONS

A hydrologic model of the Delaware River basin was developed that included the operation of reservoirs and diversions based on current management policy and infrastructure. The hydrologic model was used to examine the sensitivity of the water resources in the basin to climate change. Because of much uncertainty in predicting climate change by use of general circulation models, ranges of prescribed changes in climate were used.

Within the ranges of prescribed changes in temperature and precipitation used in the study, changes in drought frequency (as defined by streamflow and reservoir contents) were more sensitive to changes in precipitation than to changes in temperature. In contrast, changes in irrigation demand were more sensitive to changes in temperature than to changes in precipitation. The water resources of the Delaware River basin also were very sensitive to changes in stomatal resistance, which may offset the effects of increases in temperature and decreases in precipitation.

The effects of climate change on water resources in the Delaware River basin are uncertain for several reasons. First, GCM predictions of the effects of increasing CO_2 on regional precipitation are unreliable and basin water resources are very sensitive to changes in precipitation. Second, the basin water resources are sensitive to assumptions about the effects of CO_2 on stomatal resistance of plants to transpiration. Finally, the effects of natural climate variability are as large as those due to the prescribed temperature and precipitation changes. Natural variability in precipitation and temperature, therefore, may mask the effects of long-term climate trends due to human factors.

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SUMMARY OF THE UPPER MIDWEST REGION BREAKOUT SESSION

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Gregory J. Wiche, Rapporteur

ABSTRACT

The upper Midwest region is assumed to generally include the Great Lakes, the upper Mississippi River basin, the Missouri River drainage basin, the Red River of the North drainage basin, and southern parts of the Canadian provinces Alberta, Saskatchewan, Manitoba, and Ontario. Major water resources units within the upper Midwest region would include the Great Lakes, Illinois River, upper Mississippi River, Land of 10,000 Lakes (Minnesota), Missouri River, Red River of the North, and Saskatchewan River.

The climate of the upper Midwest region experiences cold winters and warm summers. Precipitation ranges from 10 inches in the semi-arid areas in the western part of the region to 40 inches in the more humid areas around the Great Lakes. Much of the precipitation falls during the growing season of April to September.

The climate in the upper Midwest region varies greatly from one part of the region to another. The Great Lakes area averages nearly 110 inches of snowfall annually due mostly to lake-effect snow squalls. The remainder of the Midwest region averages between 35 and 40 inches of snow with more in the foothills of the Rocky Mountains due to upslope conditions.

Snowpacks, a product of winter and early spring precipitation, are an important element in sustaining streamflow in late spring and early summer and in supplying ground moisture. Summer and fall storm systems supply runoff to streamflow after cessation of snowmelt runoff and periodically resupply ground moisture; however, most of the region is classified as sub-humid relative to rainfall events.

Water uses within the upper Midwest region probably cover essentially the same or similar listings that characterize the other regions: West, Southeast, and Northeast. This includes hydropower, municipal, industrial, agricultural, navigation, fish and wildlife, recreation, environmental, and ecological resources management.

The breakout session provided an opportunity to review and discuss results of regional climate-change impacts studies and possible future directions for research on climate-change sensitivities.

A theme that permeated the conference was that climate change is coming, in particular in the form of overall warming over the continent, and water resources systems and their various uses are going to be affected. The presentations and discussions during the upper Midwest session assumed warming will occur and proceeded to focus on specific water resources units within the region. The titles of the individual presentations indicate the direction as well as diversity of subject matter and geographical coverage of water resources units in the region. Titles of presentations were as follows:

- A Future-Oriented Regional Scale Assessment of the Impacts of Climate Change and of the Potential Adaptive Responses Thereto: The MINK Study

- Impacts of Climate-Change Scenarios in the Saskatchewan River Sub-Basin: Lessons for the Missouri?

- Prescriptive Reservoir System Analysis Model Missouri River System Application

- A Methodology to Estimate Global Climate-Change Impacts on Lake Waters and Fisheries in Minnesota

- The Sensitivity of Water Resources Management to Climate Change: A Great Lakes Case Study

Each presentation (all considered climate change and warmer temperatures as givens) provides specific information that was useful in obtaining an idea of the studies, analysis, and results of activities around the country. Each presentation in the order listed is summarized in the following paragraphs.

Dr. Stewart Cohen described a pilot study of water resources in the Saskatchewan River basin. The objective of this study was to provide information on impacts of global warming scenarios on changes in runoff or annual net basin water supply. Numerous scenarios were constructed and analyzed using hypothetical growth rates for irrigation, outputs from general circulation models (GCMs), and hypothetical warming cases. Results of the study indicated decreases in summer soil moisture and increases in irrigation demand (assuming present technology and crops), but were inconclusive relative to changes in annual net basin water supply. Several available GCMs were used and results compared, indicating considerable variation between models. However, all indicated a similar trend. It was pointed out that precipitation in the Rocky Mountains appeared to be a key variable in determining runoff to the Saskatchewan River, and Dr. Cohen speculated that the same variable would be important in determining runoff in the Missouri basin.

The second presentation moved from the analysis of a river basin flow network to the Great Lakes, which represent the largest surface fresh-water supply in the United States. These lakes are extremely important to the six states that surround them, to the nation, and internationally. These water resources serve many uses such as hydropower, industrial and municipal supply, navigation, recreation, and fish and wildlife resource management. Dr. Frank H. Quinn's work has used the GCM in conjunction with water balance models to analyze the impacts of warming on the net basin water supply to the Great Lakes. His findings indicate the potential, under a general warming scenario, for long-term reduction in net basin water supply to the lakes of between 23 and 51 percent. The largest potential lake-level declines would occur in Lakes Michigan and Huron and could amount to as much as 2.5 meters. Obviously, such traumatic potential in lake level would require new paradigms in management of Great Lakes water resources. Such impacts would have far-reaching effects on local, state, national, and international interests.

The third presentation moved the focus of attention from the Great Lakes to the lower portion of the Missouri River basin, namely the area encompassed by the states of Missouri, Iowa, Nebraska, and Kansas (MINK). This study focused on the impacts of a future change in climate on the total economy of the MINK region. Impacts on agriculture, forestry, water resources, and energy were emphasized. It deviated from the other studies in that historical records of the 1930s were used to provide an analogue of the kinds of potential climate change in lieu of outputs from one of the GCMs. This study reconstructed natural streamflows and adjusted them to current water management operating plans. The study methodology developed allowed for spatial and temporal variability and was considered to provide a more realistic assessment of impacts from potential future climate change.

The focus then moved from the lower Missouri River to the Land of 10,000 Lakes--Minnesota. Dr. Heinz G. Stefan presented an interesting discussion on the potential effects of future climate change on the fisheries habitat of Minnesota lakes. Methodology used to accomplish the assessment was application of a lake temperature stratification and dissolved oxygen simulation model that calculated water temperature and dissolved oxygen as a function of depth. As with other studies, outputs from a general circulation model were used to drive the analysis. In general, the results indicated a change from cold water to warm-water lakes and an increase in biomass. Questions and discussions centered on whether the extent and types of habitat would be available to support an increase in biomass and, if lake temperatures did modify to the point that habitat changed from cold water to warm water, was there an identifiable adverse impact other than reorganization of fisheries population species.

The last presentation in the session described and discussed the development and potential application of a mathematical model that could provide prioritization of individual uses through a controlled wat?. resources system that featured multiple uses.

This type of model could be quite useful in an atmosphere of intensive competition between individual uses where multiple uses are available or authorized. The model was, in fact, developed specifically for application to the current atmosphere of competition between water uses in the Missouri River basin. The potential for decreases in available water resources as a result of climate change could sharply increase competition in many other water resources systems, thus creating numerous other opportunities for beneficial use of this type model.

The presentations and discussions during the upper Midwest sessions were interesting, enlightening, and beneficial, and covered a variety of subject matter and specific geographical areas. Climate change in the form of warming was a given condition and in itself dictates that existing water resources systems are going to be stressed under such future conditions. While no one questioned the statements that climate change is coming, there was ample evidence of uncertainties about the rate and magnitude of climate change and especially about the direction of change in precipitation. Uncertainties are also associated with results of current general circulation models, a tool used extensively in the studies and analysis presented.

Relative to the questions of what happens next? or what should be done that is not currently being done, there seem to be mixed reactions. Some were convinced of change and that actions of some nature should be instituted, while others, though not disclaiming a change, would move very slowly with anticipation of more definitive and supportable estimates in the near future.

IMPACTS OF CLIMATE-CHANGE SCENARIOS IN THE SASKATCHEWAN RIVER SUB-BASIN: LESSONS FOR THE MISSOURI?

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ABSTRACT

The Saskatchewan River sub-basin, located in western Canada, is an important source of irrigation supply for agriculture in Alberta and Saskatchewan. The sub-basin includes the North and South Saskatchewan, Red Deer, Bow, and Oldman rivers (see Figure 1). Annual flow at The Pas, Manitoba, averaged approximately 650 m^3 sec^{-1} during the 1951-1980 period. Most of this originated as snowmelt from the Rocky Mountains along the western boundary of the watershed. Some additional runoff is available from the northern half of the watershed, which is mostly forested. Much of the remainder of the sub-basin south of 52°N is grassland, which contributes very little runoff.

Immediately south of the Saskatchewan sub-basin is the Missouri River sub-basin (see Figure 1). Several small tributaries, including the Milk River, extend into Canada. Streamflow at Bismarck, North Dakota, is slightly higher than that observed at The Pas, averaging about 680 m^3 sec^{-1} during the 1951-1980 period.

Both watersheds experienced below 1951-1980 average flows in the 1930s, 1956-1963, and 1985-1990 (see Figure 2). The 1987-1988 drought was particularly severe, as the Saskatchewan River's 1988 annual mean discharge was the second lowest on record. The Missouri River's flow would have been lower had it not been for additional releases from upstream reservoirs. Agriculture suffered large losses, and many farmers in North Dakota, as well as some scientists, were concerned that 1988 might be a precursor of regional climate changes associated with projected global warming; i.e., the "greenhouse effect" (Riebsame et al., 1991).

The recent report of the Intergovernmental Panel on Climate Change has concluded that increasing concentrations of carbon dioxide and other trace gases would result in a warming of the earth's climate by the middle of the next century (IPCC, 1990a). This view is consistent with those of earlier assessments (U.S. NRC, 1982; WMO, 1986).

Research on the regional impacts of *scenarios* of global warming attempts to focus global climate issues on the regional level objectively and quantitatively, building an information bridge between global-climate-change research and regional resource management. This paper reports on a recent study of the impacts of global warming scenarios on water resources in the Saskatchewan River sub-basin (Cohen et al., 1989; Cohen, 1991). Implications for the neighboring Missouri River watershed are briefly discussed.

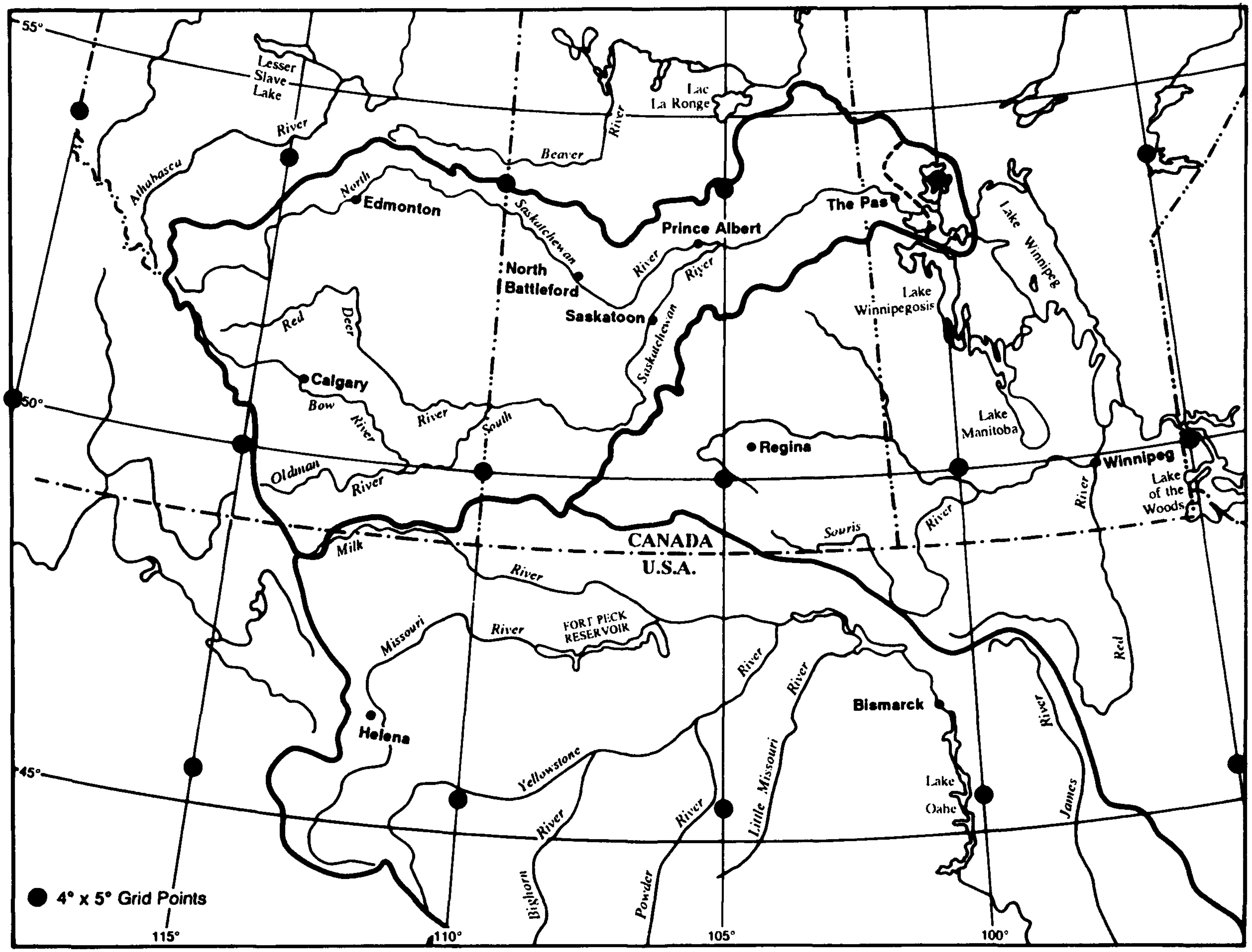

Figure 1. Sakatchewan River and Missouri River Sub Basins

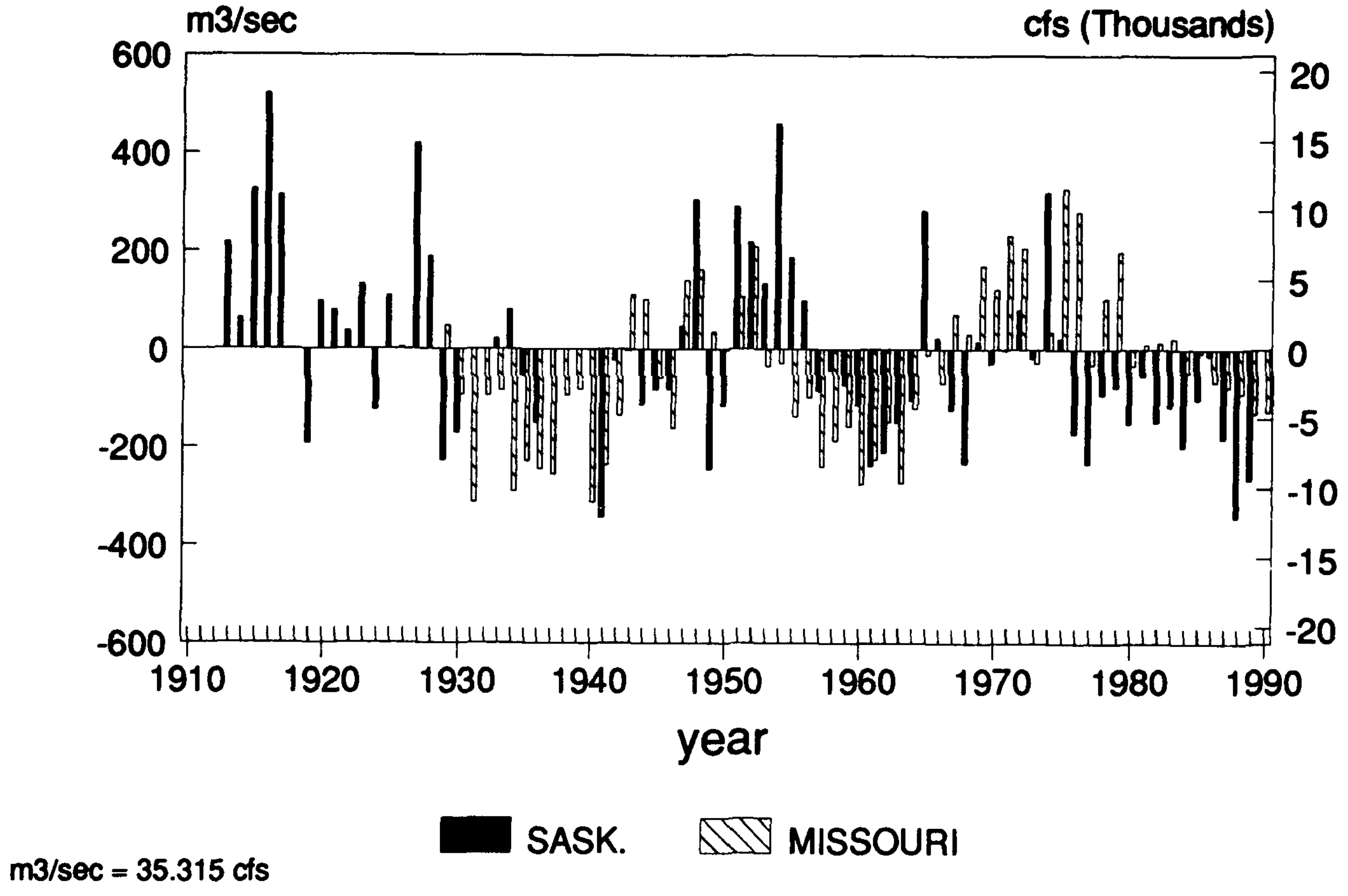

Figure 2. **Saskatchewan River and Missouri River (difference from 1951–80 mean flow).**

METHODOLOGY

Net Basin Supply

The specific research problem addressed by this case study is to determine the impacts of global warming scenarios on net basin supply (NBS), which is analogous to streamflow at the mouth of the watershed. NBS is what remains after accounting for precipitation (P), runoff (R), open-water evaporation (E), evapotranspiration (ET), infiltration, diversions (D), and consumptive use (C).

Long-term variations in groundwater are assumed to have negligible impact on NBS. There is considerable uncertainty in this assumption, but additional research is needed to determine its validity. If variations in groundwater are neglected, then

$$NBS = R - E - C \pm D \qquad (1)$$

in which R is a function of P and ET. In the Saskatchewan case, where open water covers only 1 percent of the study area, equation 1 becomes

$$NBS = R - C \pm D. \qquad (2)$$

Evaporation from reservoirs is included in C in equation 2 since it is considered by others as a "user" of water in the region (PPWB, 1982).

Water Balance and Consumptive Use

Individual components of NBS were estimated separately, using (a) a monthly version of the Thornthwaite water balance model to compute R and (b) a regression model for estimating changes in irrigation for scenarios of growth of irrigated land area. These various outputs are then substituted into equation (2).

Data requirements for the Thornthwaite approach (Mather, 1978) are minimal, in that only temperature, precipitation, latitude (a surrogate for radiation), and soil moisture storage capacity are used as inputs. However, this procedure does not account for the effects of wind, changes in the energy budget, and possible CO_2 enrichment of plants, all of which could influence ET rates.

The Thornthwaite model produces estimates of R (i.e., soil moisture surplus), ET, and soil moisture deficit. In the case study, estimates of basin R were obtained from a weighted sum of R estimates for each grid cell. For the Saskatchewan sub-basin, weighting was dictated by the percentage of the basin's "effective" drainage area found in each cell. The "effective" area is defined as land that could provide R for any precipitation event with a return period of 2 years or more (Mowchenko and Meid, 1983).

Another important limitation is that the above combination of separate models is not an integrated approach as one could achieve within a single model of basin hydrology (Croley, 1990), so assumed changes in certain parameters (e.g., lake temperature) may not be consistent with other hydrometeorological changes that may be taking place under these scenarios. However, the data limitations and assumptions of initial input values for calibration can affect the performance of all-inclusive basin models as well (Gleick, 1989). Impacts modeling is a long-term research issue, and the choice of simple or sophisticated modeling approaches will continue to be influenced by data availability as well as spatial resolution of general circulation models (GCMs), the leading source of information for constructing scenarios of global warming.

Estimates of future C were obtained from several sources. The Saskatchewan study used a simple regression-based model of irrigation demand to estimate future C/hectare for the various climate-change scenarios of soil moisture deficit obtained from the Thornthwaite output. Data on other water uses were obtained from the Prairie Provinces Water Board (PPWB, 1982). These uses were assumed to remain unchanged.

Scenarios of Regional Climate Change

Fifteen scenarios were used in this study. A series of ten 2°C and 4°C hypothetical warming scenarios were used. The other five were derived from GCM outputs: (1) two interpolations of a Goddard Institute for Space Studies (GISS) GCM simulation, labeled GISS84 and GISS87; (2) two versions of the Geophysical Fluid Dynamics Laboratory (GFDL) model, labeled GFDL80 and GFDL86; and (3) output from the Oregon State University (OSU) model (Cohen, 1991a). Temperatures were higher in all months. Precipitation was higher in GISS and OSU, while GFDL80 and GFDL86 exhibited declines in fall/winter and summer, respectively (Cohen, 1991a).

In the case study, empirically interpolated sets of temperature and precipitation data were used. They contained mean monthly gridded data for the 1951-1980 "normal" and the various scenarios. These were used as inputs for the Thornthwaite water budget. Time series data for scenarios and observations for the common grid points were not available. Thus, in the control runs, "normal" monthly climate data were used to simulate "normal" annual runoff. When consumptive use was accounted for, the simulated "normal" NBS was within 5 percent of the observed 1951-1980 mean streamflow.

For climate-change scenarios, monthly air temperatures were raised according to the GCM outputs and hypothetical warming of 2°C and 4°C. Monthly precipitation values were altered by GCM outputs and hypothetical changes of -20, -10, 0, +10, or +20 percent. Wind speed and humidity were assumed to remain at present levels.

Several uncertainties related to global warming scenarios are inherent in regional-scale climate impacts research (Cohen, 1990). One is the accuracy of the GCMs themselves. An example is the tendency for some GCMs' control runs to overestimate present winter precipitation in the Rocky Mountains (Kalkstein, 1991). Impacts researchers assume that despite the errors exhibited in the GCMs' control runs, these models can provide a reasonable response to simulated atmospheric perturbations (i.e., 2 X CO_2). The conventional approach has been to use station observations as the baseline data set, rather than the GCM control runs, so as to preserve the unique regional features of the study areas' climates. The difference between the control run and the 2 X CO_2 experiment is then "added" to this baseline.

A second problem is related to the GCMs' coarse spatial resolution (typical grid cell dimensions are 4°-5° latitude X 5°-10° longitude), which does not represent subcontinental features very well, including the Rocky Mountains. A third problem concerns the spatial representativeness of the scenario outputs *and* the station observations that constitute the baseline. In areas of complex terrain, stations probably represent little more than the points upon which they are situated, while GCM output for a particular grid cell is actually an areal average for simplified terrain. This mismatch has generally been ignored, and perhaps it is safe to do so in some cases (given the other uncertainties). However, the estimation of streamflow is dependent on precise knowledge of spatial precipitation patterns, and this mismatch is likely to hinder validation efforts. In some studies, stations have been paired with the nearest GCM grid point, which may have been quite distant. In this case as well as others, GCM and station output were interpolated to a common grid (Cohen, 1990, 1991b).

RESULTS

Mixed results were obtained for runoff for five GCM-based scenarios in the Saskatchewan sub-basin (see Figure 3), primarily because of differences in scenario projections at the Rocky Mountains grid cell. The hypothetical cases demonstrated that warming would lead to reduced runoff unless increased precipitation occurred.

Soil moisture deficits were projected to worsen in four of the GCM-based scenarios. The exception was GFDL80, the oldest of the GCMs used in this study. Deficits were higher in all 10 hypothetical cases. Such increased deficits are consistent with soil moisture simulations for the Prairies and Great Plains regions of North America obtained directly from GCMs (Kellogg and Zhao, 1988).

The regression model described earlier was used to project changes in consumptive use resulting from changes in soil moisture deficit, assuming present crop types, irrigation technology, and market conditions. The increased deficits, combined with increased irrigated land area, resulted in higher consumptive use even though all other uses, including reservoir evaporation, were assumed to remain constant (see Figure 4). In the GFDL80 scenario, there was a smaller increase as the reduced deficit partially compensated for the increase in irrigated land area. GFDL87 and the 4°C hypothetical cases with reduced precipitation resulted in increases of greater than 100 percent over the base case.

Table 1 summarizes NBS results for the GCM-based and hypothetical warming scenarios. In the Saskatchewan River sub-basin, there was no consensus among the GCM-based scenarios, despite the projected increases in consumptive use, because of the differences in projections of runoff noted above. This illustrates the need for improved monitoring and modeling of precipitation in the Rocky Mountains.

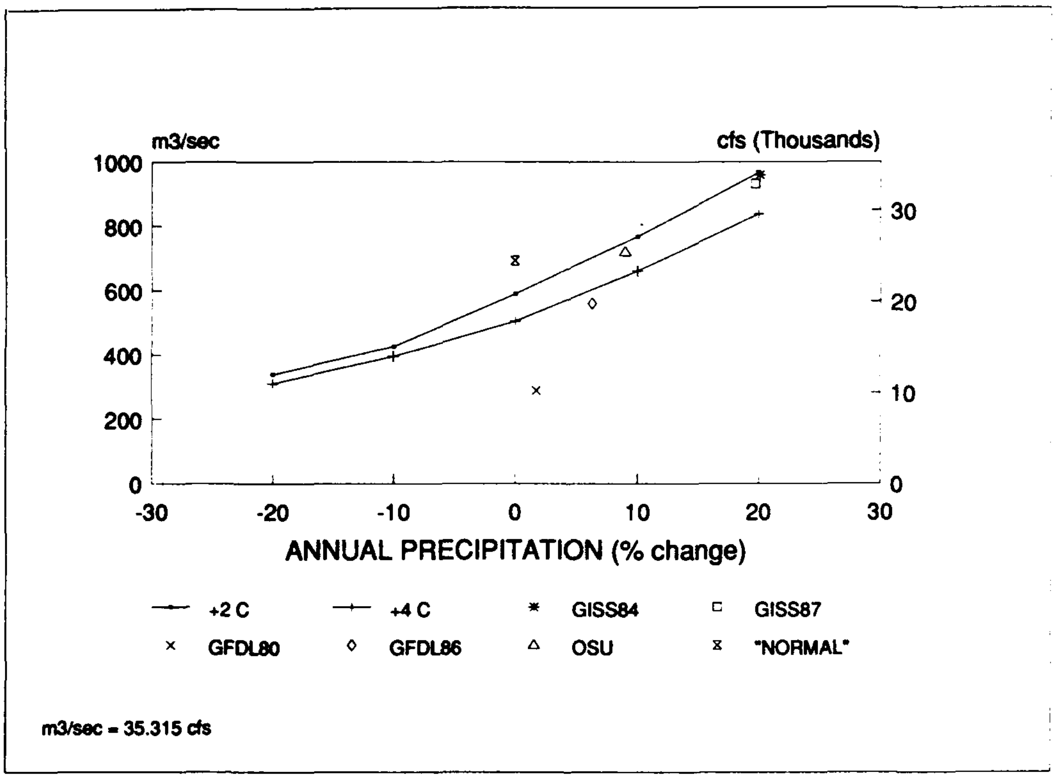

Figure 3. **Impacts on annual runoff (Saskatchewan River).**

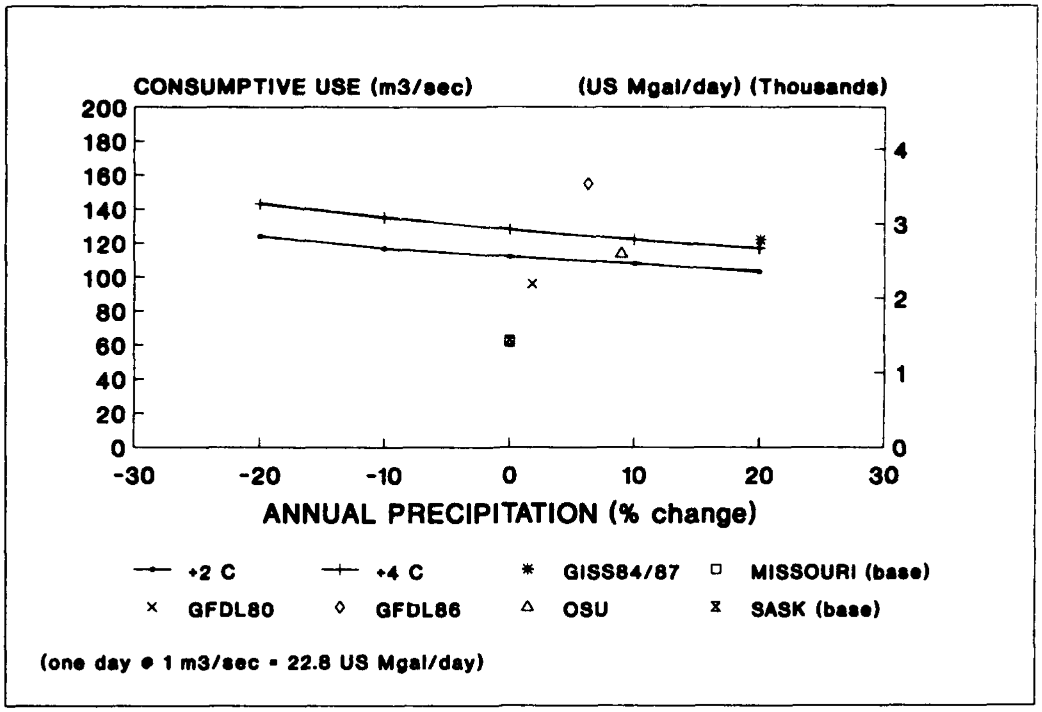

Figure 4. **Impacts on annual consumptive use (Saskatchewan River high irrigation scenario).**

Table 1.

Projected Changes in Net Basin Supply (%)

	LOW	HIGH
GISS84	40.0	33.2
GISS87	35.5	28.7
GFDL80	-65.2	-70.1
GFDL86	-27.3	-36.1
OSU	2.4	- 3.9
T2/-20P	-59.7	-66.6
T2/-10P	-44.9	-51.4
T2/N	-18.3	-24.4
T2/+10P	10.6	4.8
T2/+20P	43.0	37.6
T4/-20P	-66.1	-74.2
T4/-10P	-51.7	-59.3
T4/N	-33.4	-40.7
T4/+10P	- 7.9	-14.6
T4/+20P	21.0	14.6

NOTES: LOW = 300000 ha (+20%) irrigated lands.
HIGH= 500000 ha (+100%) irrigated lands.

SOURCE: Adapted from Cohen (1991a).

IMPLICATIONS FOR THE SASKATCHEWAN AND MISSOURI WATERSHEDS

If global warming occurs, water users will respond depending on their sensitivity to climate. Water supply systems are most sensitive to reduced runoff where demand closely matches or exceeds typical supply (Riebsame, 1988). Increased irrigation is one option, but there are others that have not been addressed in this case study.

Within the Saskatchewan sub-basin, the North and South sub-basins are currently or in prospect of experiencing serious water scarcities (Tate, 1986). The Canadian portion of the Milk sub-basin, part of the Missouri system, is in similar circumstances (Tate, 1986). A recent study of the Oldman sub-basin in southern Alberta concluded that a warming of 2°C with no change in precipitation would lead to irrigation supply shortages unless the sub-basin's apportionment agreement was to be met by other systems (such as Bow River), which may be subject to similar stresses themselves (Byrne et al., 1989).

A recent study of U.S. water resources identified the Missouri sub-basin as one of the most vulnerable U.S. watersheds due to high water demand relative to supply, high variability of streamflow, high dependence on hydroelectricity, and groundwater supplies that are experiencing overdraft (Waggoner, 1990). A study of the South Platte sub-basin (near 40°N) concluded that dryland agriculture and in situ water users (such as navigation and hydroelectric power production) may experience greater risks and poorer economic returns if global warming occurs (IPCC, 1990b). Since GCM simulations of greenhouse climates generally show similar changes in the northern Great Plains and the southern prairies of Canada, results obtained for the Saskatchewan sub-basin may therefore be relevant to the Missouri.

CONCLUSIONS

Case studies such as these represent steps in building the information bridge between global and regional/local interests. Uncertainties are recognized throughout this process. Nevertheless, important information on regional sensitivities to global warming has been obtained, thereby providing some preliminary direction for researchers and decision-makers. *Of particular importance in this case is that the probabilities of hydrologic drought (and flooding?) and agricultural drought may not change in the same way.* This information may not be enough on its own to convince regional authorities of the need to respond, but the alternative is to wait until the global warming "signal" is unambiguously detected. Given the long lead times required for construction of facilities and negotiation of water-related management agreements, and their long lifetimes once they are in place, global warming should be considered now.

In parallel with continuing efforts to improve GCMs, additional research on regional impacts will be needed to meet growing demands for information related to multi-sectoral feedbacks and adaptive responses to global warming. This will require a long-term interdisciplinary effort at impact model development, much of which will be region specific. Such efforts will be enhanced by the development of climate scenarios for regional applications, and by new research partnerships involving expertise from within and outside the region of interest. Following a recommendation from a recent United States-Canada symposium on impacts in the North American Great Plains (Wall, 1991), it is anticipated that a major binational interdisciplinary study will be initiated in the near future.

ACKNOWLEDGMENTS

My thanks to K. Czaja for drafting Figure 1, and to G. Wiche of the U.S. Geological Survey, Bismarck, for providing data on discharge and consumptive use for the Missouri sub-basin at Bismarck and a map of the Missouri watershed. Other acknowledgments of assistance during various stages of the case study are in Cohen (1991a). The views expressed herein are my own and are not necessarily those of Environment Canada.

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PRESCRIPTIVE RESERVOIR SYSTEM ANALYSIS MODEL MISSOURI RIVER SYSTEM APPLICATION

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ABSTRACT

A reservoir system analysis model has been developed that is based on determining prescriptive operations for use by water managers in the U.S. Army Corps of Engineers. The model, coined HEC-PRM, represents the reservoir system as a network and uses network-flow programming to allocate optimally the system water. The goals of and constraints on system operation are represented with system penalty functions. The objective function of the network problem is the sum of convex, piecewise linear approximations of these penalty functions. The solution is the optimal allocation of water in space and time for the system based on minimizing the total system penalty. The results are processed to display time series of reservoir releases, reservoir storage volumes, channel flows, and other pertinent information. The model has been tested successfully on the Missouri River system. Operation purposes include hydroelectric power, instream and reservoir recreation, navigation, flood control, instream and reservoir water supply, and environmental goals and constraints. Analyses are performed for period-of-record monthly flow sequences. In climate-change studies, it is proposed that the model be applied for hydrologic time series representing present conditions, then successively applied for hydrologic time series representing changed future conditions. Value (penalty) functions could also be altered to reflect future preferences.

PROBLEM DESCRIPTION

The Missouri River mainstem reservoir system consists of six reservoirs: Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. According to the reservoir regulation master manual (USACE, 1979), the mainstem system is operated "...for flood control, navigation, irrigation, power, water supply, water quality control, recreation, and fish and wildlife." Current operation priorities in operating the reservoirs to meet these objectives are described as follows in the regulation manual (pages IX-1 and IX-2):

> *First*, flood control will be provided by insuring vacant space at the beginning of each year's flood season; *second*, all irrigation, and other upstream water uses will be allowed for; *third*, downstream M&I water supply and water quality requirements will be provided for; *fourth*, the remaining water supply will be regulated for equitable service to navigation and power; *fifth*,...the efficient generation of power; and *sixth*, the reservoirs will be operated for maximum benefit to recreation, fish and wildlife.

A review of these priorities was prompted by the following (USACE, 1990a):

> (1) It has been 10 years since the last [manual] update, (2) the current (3-year) drought has pointed out that parts of the existing Master Water Control Manual may require change, (3) recreation on the reservoirs and the river downstream is becoming an increasingly important industry, (4) the current drought has demonstrated the importance of Missouri River water to commercial navigation, and (5) the Master Water Control Manual needs to be updated to include regulation criteria for endangered and threatened species, new data collection methods, and flood history which has occurred since the last update.

To review the priorities in a systematic fashion, an analysis tool is required. This tool must evaluate system operation for all purposes in terms of hydrologic, economic, and environmental efficiency.

Analysis tools appropriate for the Missouri River reservoir mainstem study may be classified broadly as descriptive or prescriptive tools. Descriptive tools typically simulate operation with a specified operation policy. The alternative policies considered are proposed by a user, or an alternative-generating scheme. A prescriptive tool, on the other hand, relies on a formal definition of the goals of and constraints on system operation to define best system operation. It automatically nominates the alternative policies to be considered. It evaluates the feasibility of each with a built-in simulation model. With a formal definition of operation goals and objectives, it quantifies the efficiency of each feasible alternative. Finally, after considering all alternatives, it identifies the best policy. Examples of prescriptive tools are linear-programming models, non-linear-programming models, and dynamic-programming models.

PROPOSED SOLUTION

The solution considers the reservoir operation planning problem as one of optimal allocation of available water. The proposed solution to this water allocation problem is as follows:

- Represent the physical system as a network
- Formulate the allocation problem as a minimum-cost network-flow problem
- Develop an objective function that represents desirable operation
- Solve the network problem with an off-the-shelf solver
- Process the network results to define, in convenient terms, system operation

Represent System as a Network

For solution of the water allocation problem, the reservoir system is represented as a network. A network is a set of arcs that are connected at nodes. The arcs represent any facilities for transfer of water between two points in time or space. Network arcs intersect at nodes. The nodes may represent actual river or channel junctions, gauge sites, monitoring sites, reservoirs, or water-demand sites. Flow is conserved at each node: The total volume of water in arcs originating at any node equals the total volume in arcs terminating at that node.

Figure 1 illustrates a simple network representation. Node 3 represents a reservoir. Node 4 represents a downstream demand point. Two additional nodes with associated arcs are included to account completely for all water entering and leaving the system. Node 1 is the source node, a hypothetical node that provides all water for the system. Node 2 is the sink node, a hypothetical node to which all water from the system returns. The arc from

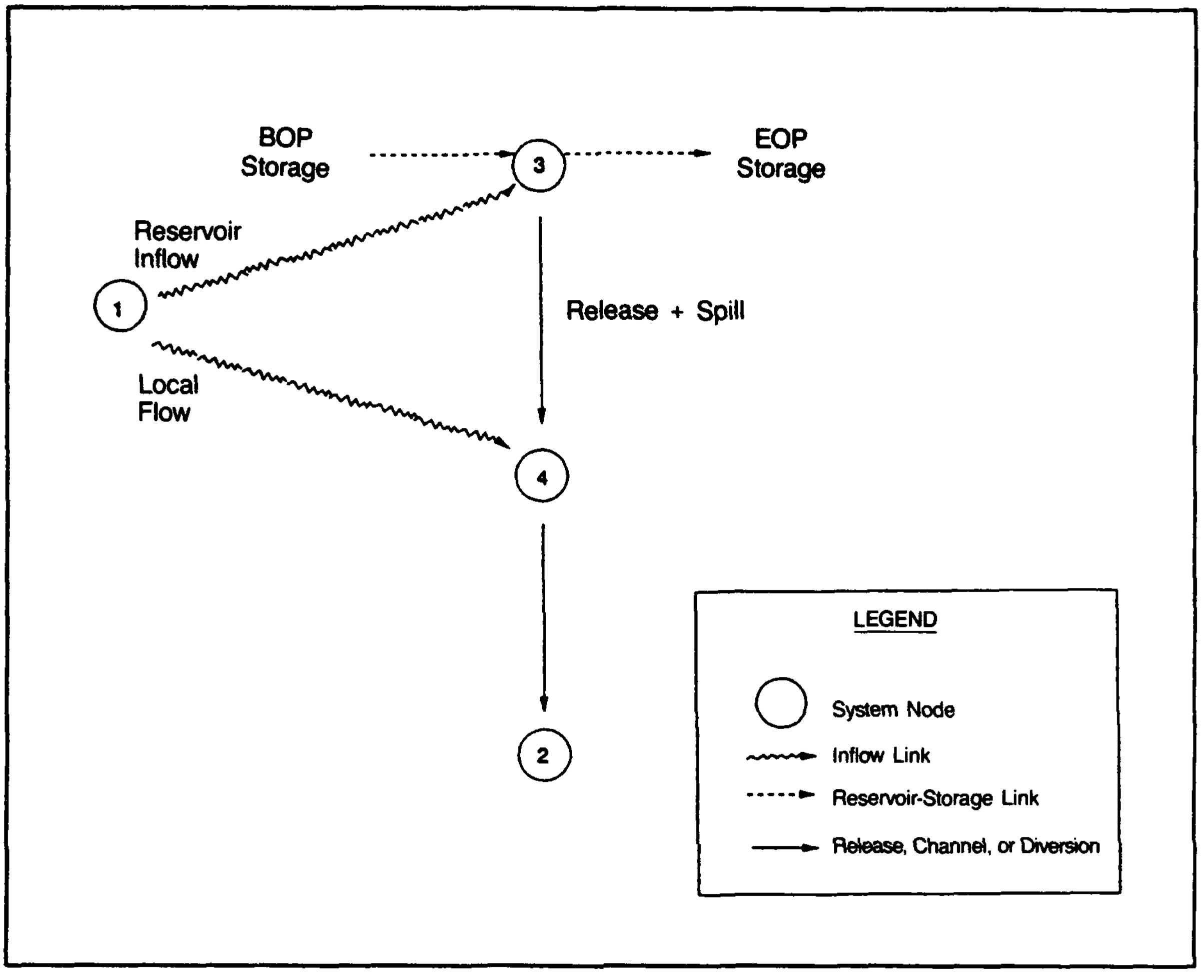

Figure 1. **Simplified single-period network.**

node 1 to node 3 represents the reservoir inflow. The arcs shown as dotted lines represent the beginning-of-period (BOP) and end-of-period (EOP) storage in the reservoir. The BOP storage volume flows into the network from the source node. The EOP volume flows from the network back to the sink node. The arc from node 3 to node 4 represents the total reservoir outflow. The arc from node 1 to node 4 represents the local runoff downstream of the reservoir. The arc from node 4 to node 2 carries water from the reservoir/demand point network to the sink.

To analyze multiple-period system operation, a layered network is developed. Each layer represents 1 month. To develop such a layered network, the single-period network representation is duplicated for each time period to be analyzed. The duplicate networks are connected by arcs that represent reservoir storage.

Formulate the Allocation Problem as a Minimum-Cost Network-Flow Problem

The goals of and constraints on water allocation within the reservoir system can be represented in terms of flows along the arcs of the network. If a unit cost is assigned for flow along each arc, the objective function for the network is the total cost for flow in all arcs. The ideal operation will be that which minimizes this objective function while satisfying any upper and lower bounds on the flow along each arc. The solution also must maintain continuity at all nodes. A network solver finds the optimal flows for the entire network simultaneously, based on the unit cost associated with flow along each arc. The functions that specify these costs are defined by the analyst.

The simplest cost function is a linear function. Such a function represents the cost for flow along one arc of a network. The cost increases steadily as the flow increases in the arc. The unit cost is the slope of the function. It may be positive or negative. The total cost for flow along the arc represented is the product of flow and the unit cost. The simplest linear function is too simple to represent adequately many of the goals of reservoir operation. Instead, a nonlinear function, such as that shown in Figure 2, may be required.

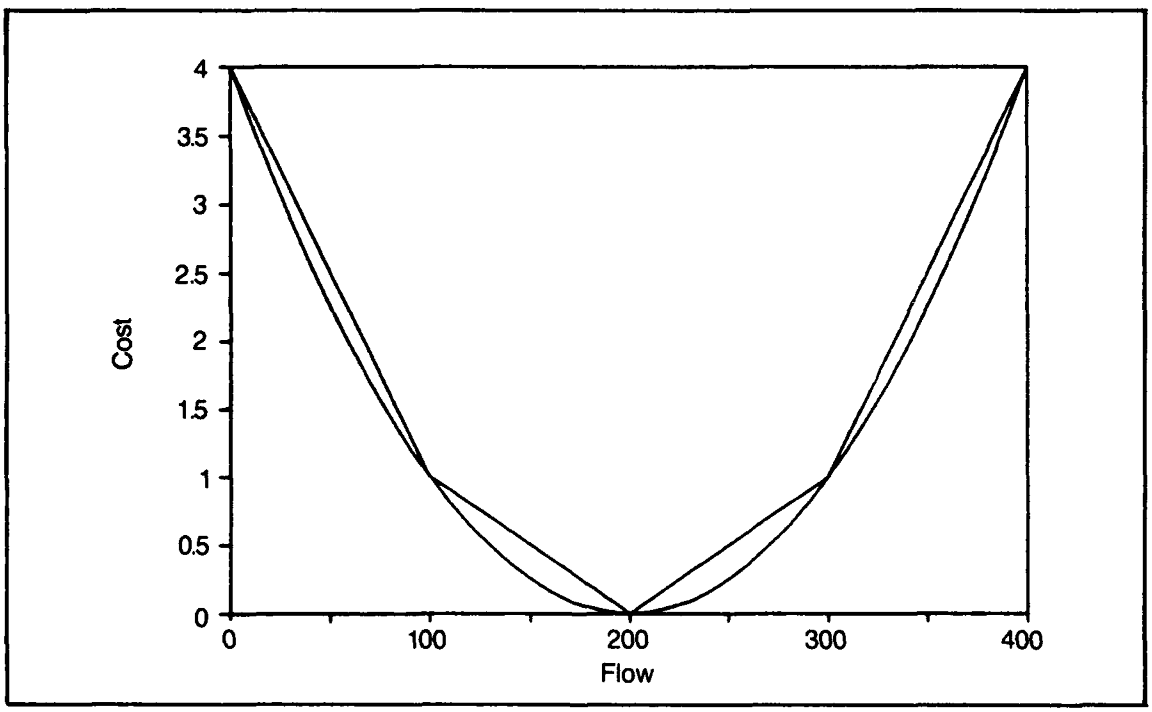

Figure 2. **Piecewise linear approximation of nonlinear penalty function.**

Convex cost functions can be approximated in a piecewise linear fashion for the proposed network model. Figure 2 illustrates piecewise approximation of a complex cost function. Linear segments are selected to represent the pertinent characteristics of the function. The analyst controls the accuracy of the approximation. More linear segments yield a more accurate representation, but increase the complexity and time for solution of the resulting network-flow programming problem. Thus, as the approximation improves, the time for solution increases. Jensen and Barnes discuss this approximation in detail (1980, pages 355-357).

With a piecewise linear approximation, the physical link for which the function applies is represented in the network by a set of parallel arcs. One arc is included for each linear segment of the piecewise approximation.

Develop Objective Function Representing Desirable Operation

While desirable, it is unlikely that all goals of system operation can be represented adequately with economic costs. Some of the goals are socially, environmentally, or politically motivated. Consequently, the objective function for the proposed model is formed from penalty functions, rather than strictly cost functions. These penalty functions are in commensurate units, but those units are not necessarily dollars. The penalty functions represent instead the relative economic, social, environmental, and political penalties associated with failure to meet operation goals. Thus, even if failure to meet, for example, an environmental operation goal has no measurable economic cost, the penalty may be great.

All operation goals related to reservoir release, channel flow, or diversion flow are expressed with flow penalty functions. These functions may represent operation goals for navigation, water supply, flood control, or environmental protection. All reservoir-operation goals uniquely related to storage are expressed through penalty functions for arcs that represent reservoir storage. These functions may represent operation goals for reservoir recreation, water supply, or flood control.

Penalty functions are developed for various purposes for stream reaches and reservoirs as needed. If two or more penalty functions apply to a single stream reach or to a single reservoir, the functions are combined to yield a single penalty function. The combined penalty function then is used in the optimization. For example, a reservoir hydropower capacity penalty function, a reservoir recreation penalty function, and a water supply reservoir penalty function may apply for a reservoir. To combine the functions, the various penalties for a given storage are added. The resulting function is then edited or smoothed to yield a convex function. This convex function then is represented in a piecewise linear fashion for the network. Figure 3 illustrates this.

Solve the Network Problem with an Off-the-Shelf Solver

The optimization problem represented by the network with costs associated with flow can be written as follows (Jensen and Barnes, 1980):

$$\text{Minimize:} \quad \sum_{k} h_k f_k \tag{1}$$

$$\text{subject to:} \quad \sum_{k \in M_O} f_k - \sum_{k \in M_T} a_k f_k = 0 \quad \text{(for all nodes)} \tag{2}$$

$$l_k \le f_k \le u_k \quad \text{(for all arcs)} \tag{3}$$

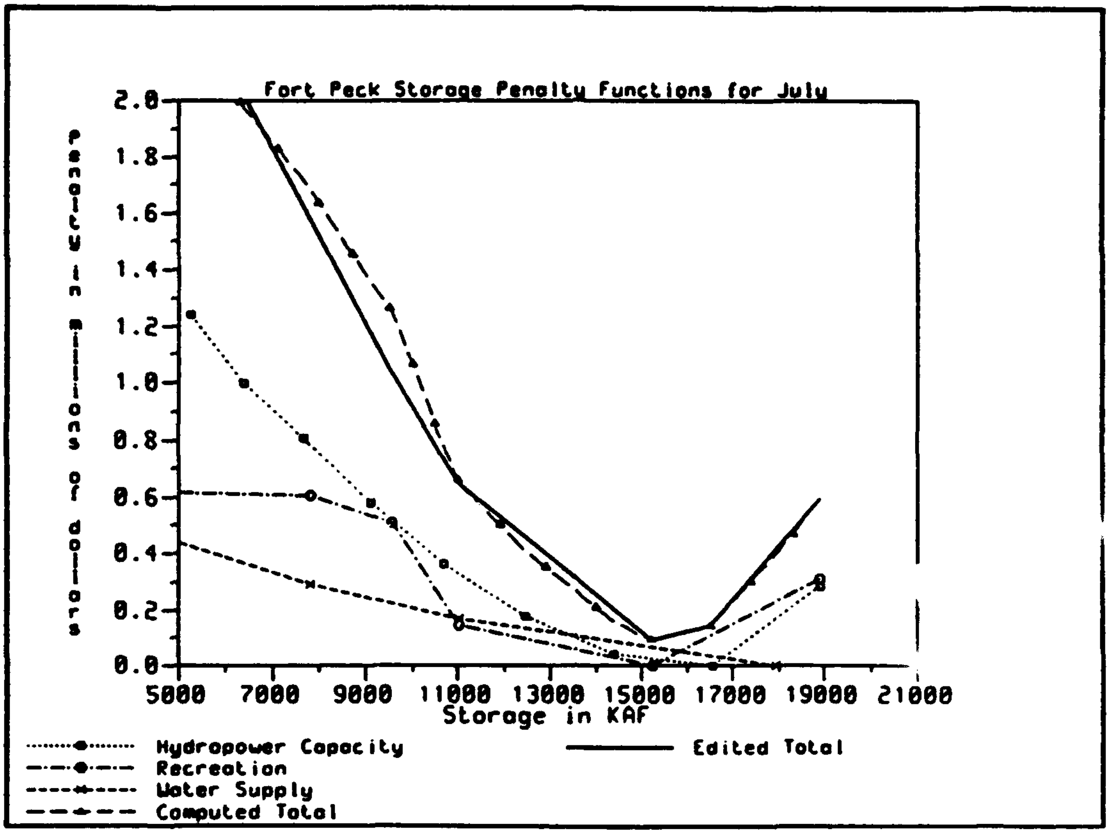

Figure 3. **Penalty functions combined.**

in which:

m	=	total number of network arcs
h_k	=	unit cost for flow along arc k
f_k	=	flow along arc k
M_O	=	the set of all arcs originating at a node
M_T	=	the set of all arcs terminating at a node
a_k	=	multiplier for arc k
l_k	=	lower bound on flow along arc k
u_k	=	upper bound on flow along arc k

Equations 1, 2, and 3 represent a special class of linear-programming (LP) problem: the *generalized minimum-cost network-flow problem*. Solution of the problem will yield an optimal allocation of flow within the system.

The optimal allocation of water in the layered network is determined with a network solver. The solver used at present implements an algorithm developed by Jensen et al. (1974), and documented and applied by Martin (1982). The solver finds the flow along each network arc that yields the total minimum-penalty circulation for the entire network, subject to the continuity and capacity constraints. These flows are translated into reservoir releases, hydropower generation, storage volumes, diversion rates, and channel flows and are presented in reports and displays. For convenience, the results after translation are stored with the HEC data storage system, HECDSS (USACE, 1990b). The results can be displayed or processed further as needed to provide information required for decision-making.

MODEL-BUILDING SOFTWARE

The software to implement the network model is general purpose and is referred to herein as the Hydrologic Engineering Center Prescriptive Reservoir Model, or HEC-PRM. With HEC-PRM, an analyst can define the layout of any existing or proposed reservoir system. Further, the analyst can describe the physical features of the system reservoirs and channels and the goals of and constraints on their operation. The operation goals can be defined by penalty functions associated with flow, storage, or both.

To permit representation of any reservoir system as a network, the software includes the following model-building components:

- Inflow link
- Diversion link
- Channel-flow link
- Simple reservoir-release link
- Hydropower reservoir-release link
- Reservoir-storage link
- Initial-storage link
- Final-storage link
- Nodes at which links are connected

By selecting the appropriate links and the manner in which they are interconnected, the analyst can describe any system. By describing the characteristics of the links and the penalties associated with flow along the links, the analyst can define operating constraints and goals.

MISSOURI RIVER SYSTEM APPLICATION

The Missouri River system model development and application is documented in a report published by HEC (USACE, 1991). The network representation of the Missouri River mainstem system includes six reservoir and six nonreservoir nodes, as shown by Figure 4. The reservoir nodes represent Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. The nonreservoir nodes represent Sioux City, Omaha, Nebraska City, Kansas City, Boonville, and Hermann.

An inflow link terminates each period at the Fort Peck, Garrison, Oahe, Fort Randall, and Gavins Point reservoir nodes. There is no local inflow into Big Bend Reservoir and therefore there is no inflow link to that node. An inflow link terminates each period at all nonreservoir nodes. An initial-storage link terminates at each reservoir node in the first period of analysis. The network ends with a diversion link at Hermann each period. A final storage link originates at each reservoir node in the final period of analysis. Channel-flow links connect the six nonreservoir nodes each period. A reservoir-release link connects each reservoir node with the next downstream node each period. Storage in each reservoir each period is represented with a reservoir-storage link.

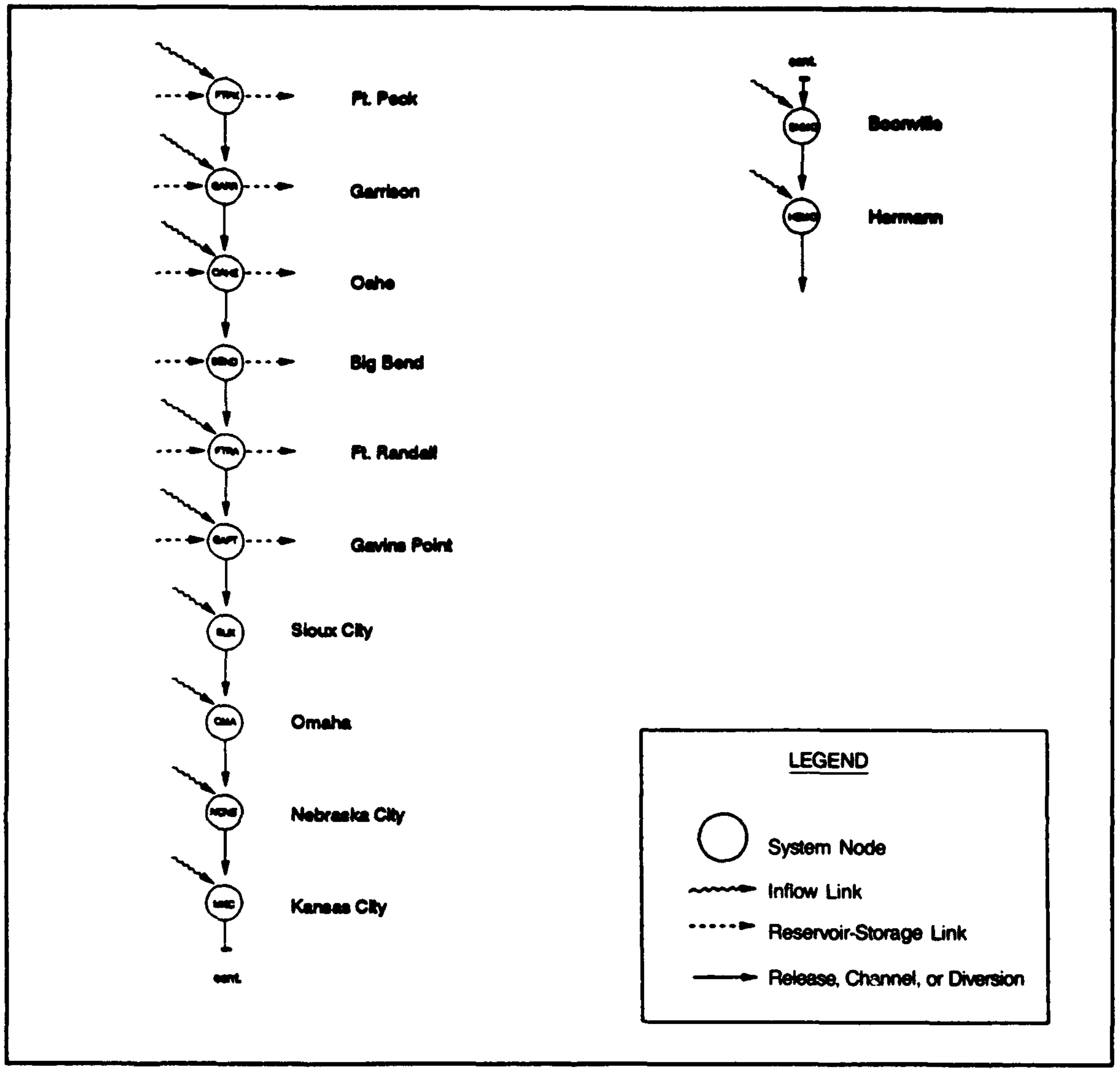

Figure 4. **Single-period link-node representation of Missouri River system.**

Goals of and constraints on Missouri River reservoir system operation are represented with system penalty functions. Procedures for developing these functions are documented (USACE, 1990c). Penalty functions are of two types: cost-based or non-cost-based. The cost-based functions, "...show the loss in economic value as the flow in each model link deviates from the optimum flow" (USACE, 1990c). For the Missouri River application, individual economic cost-based penalty functions were developed for the following outputs: urban and agricultural flooding, water supply, recreation, hydropower, and navigation. These functions vary by month if appropriate. Non-cost-based penalty functions represent goals of system operation that cannot be quantified in economic terms. For example, a flow requirement for fish and wildlife protections may be represented with a penalty function in which the penalty arbitrarily is set to force the desired operation. Only cost-based functions have thus far been used in the Missouri studies.

PHYSICAL SYSTEM AND HYDROLOGIC DATA

The Missouri River basin is 530,000 square miles with mean annual runoff of about 24 million acre-feet. Historically, annual runoff has varied from a low of 11 million acre-feet, to a high of 40 million acre-feet. Monthly volumes for the inflow links shown in Figure 4 for the 92-year historic record were compiled. These data are adjusted for upstream and local depletions to reflect 1975 conditions. Selected periods of this record are used in analyses as described later. Table 1 summarizes data on the mainstem reservoirs.

MODEL VALIDATION

Unlike a descriptive model, a prescriptive model cannot be validated directly by comparison with an observed data set. No such data set can exist because historical operation is never truly optimal for the objective function used in the model, and the objective function used in the model never reflects exactly all goals of and constraints on operation. Model logic, input data, and solution algorithms can be scrutinized. This was done. In addition, model validity was explored by applying HEC-PRM to analysis of a meaningful period, comparing the results to operation with current rules, and critically assessing the differences.

TABLE 1
Reservoir Storage Information

Reservoir (1)	Top Inactive Storage, in 1,000 Acre-ft (2)	Top Carryover, Multiple-Use Storage, in 1,000 Acre-ft (3)	Top Flood Control & Multiple-Use Storage, in 1,000 Acre-ft (4)	Top Exclusive Flood Control Storage, in 1,000 Acre-ft (5)
Fort Peck	4,211	14,996	17,714	18,688
Garrison	4,990	18,210	22,430	23,924
Oahe	5,451	19,054	22,240	23,337
Big Bend	1,696	-	1,813	1,873
Fort Randall	1,568	3,267	4,589	5,574
Gavins Point	340	-	432	492

MRD system operation was analyzed with HEC-PRM for a 5-year average flow period, March 1965 to March 1970. Hydrologic data include monthly reservoir inflows and local flows, depletions, and lake evaporation rates. Initial- and final-storage values for the mainstem reservoirs are identical to those used with the reservoir simulation model in use by the Corps Missouri River Division (MRD), applied to the same period.

Composite, piecewise linear penalty functions were developed for all purposes at all locations. Only economic (cost-based) penalty functions are used. Maximum reservoir storage was limited to the top of the annual flood control and multiple-use zone. Minimum storage was limited to the top of the inactive pool.

To test the reasonableness of the results, HEC-PRM results were compared with those of the MRD reservoir simulation model. This comparison is intended only to identify obvious shortcomings of HEC-PRM, inexplicable results, or weaknesses that would render HEC-PRM unacceptable for further analyses. A perfect match of results was not expected. Indeed, the results should not be identical, as the models employ different simplifications of the real system and operate for different goals. The MRD model follows existing operation rules, and HEC-PRM operates to minimize total system penalty for the period.

As a consequence of the validation test, HEC-PRM was accepted for subsequent analyses. It is clear from the test results that the model does what it is supposed to do: It defines a minimum-penalty allocation of system water. The test also reveals the sensitivity of the model to the penalty functions used, an expected result.

MODEL APPLICATION

Two applications of HEC-PRM have been completed and published to date: (1) analysis of the critical period for the system with the best currently available estimates of system penalty functions and (2) analysis of the same critical period with a hypothetical substantially increased navigation penalty function for Sioux City flow. The reservoir-storage levels, reservoir releases, and downstream flows were computed and compared. Figure 5 is a plot of reservoir storage for the critical period. Other plots of reservoir releases, downstream flows, stream reach, and penalty values were developed and compared, but are omitted here to conserve space. The results of the analysis of the critical period for the system with the best currently available estimates of the system penalty functions are shown as solid lines. The results of the analysis with inclusion of the hypothetical navigation penalty function are shown dashed for all plots.

The critical period for the system was identified as March 1930 to March 1949. This includes the 12-year (1930 to 1941) drought of record and the period required for refilling of reservoirs when following current operation policy. These data include reservoir inflows and local flows, depletions, and lake evaporation rates. As a rule, energy generation dominates the operation. HEC-PRM proposes release of water to drive the energy penalty to zero if sufficient water is available. Otherwise, it proposes making no release and storing water for subsequent use. This is again a case of long-term versus short-term-operation decision-making. The model must choose between making minimum releases for hydropower use now or storing water for use later. It chooses the latter based on total system penalty, as defined by the penalty functions. Although a skilled operator might choose a less drastic operation, the penalty functions used in this application do not indicate that another policy is better, although it may be as good.

In the second application of HEC-PRM, operation was analyzed for the same period described in the previous section. A hypothetical navigation penalty function was added to demonstrate the impact of system operation for high-penalty downstream requirements. The hypothetical navigation penalty function causes the flow pattern at Sioux City to be smoother, as the range of flows there is reduced and thus draws on more storage. Often the system has operated to provide exactly the minimum-penalty flow during April to November. For

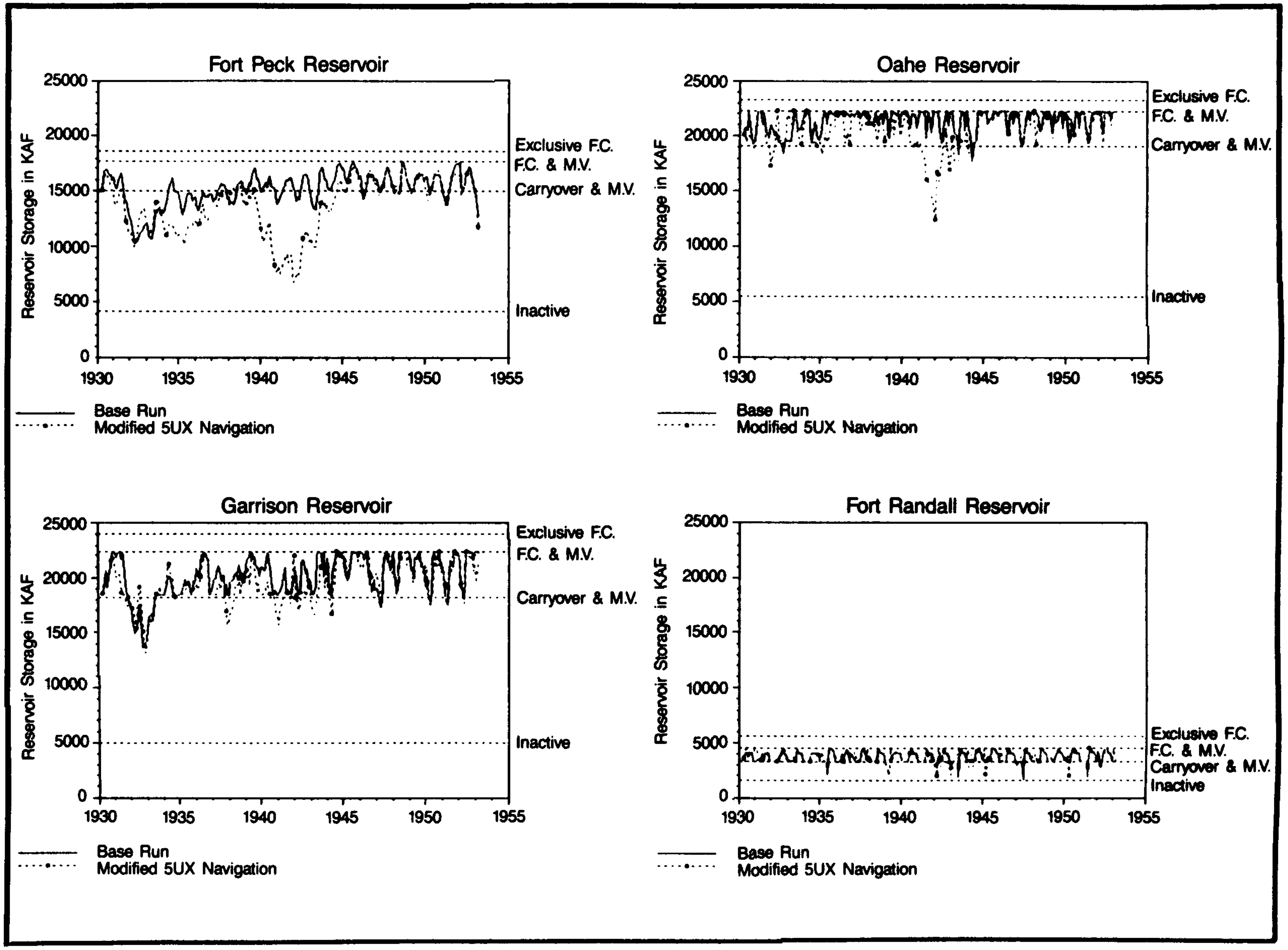

Figure 5. **Reservoir storages for critical period analysis.**

December to March, the system has reduced releases to a bare minimum to conserve water to meet subsequent April-to-November demands. Even so, to satisfy the minimum at Sioux City, the system must draw down Fort Peck, Garrison, and Oahe, starting in 1939. Earlier and later in the critical period, the Fort Peck storages are approximately the same with and without the function. Then sufficient water is available to meet the demand without drawing on upstream storage.

MODEL STATUS, FUTURE DEVELOPMENT

HEC-PRM was to be delivered to MRD in working version form in a workshop in December 1991. The model is now usable with assistance by HEC. Preliminary user documentation is also available. MRD will be applying the model early in 1992, in studies contributing to update of the Missouri River Main Stem Master Water Control Manual. The model is intended to be used to provide insight into tradeoffs between water storage and release allocation alternatives. Together with complementary studies under way using the MRD simulation model, updated systemwide operation rules will be derived to guide reservoir-operation decisions in the coming years.

A similar application to the Columbia River system commenced in January 1991. Additional model development will improve the hydropower representation (to include nonlinearity in head, flow, and power functions), update the solver to state-of-the-art capabilities, and implement a user shell to facilitate ease of data entry and display; and will implement general-purpose post-processor reporting and display capabilities. The Columbia River system application will conclude in the fall of 1992.

Current plans are that a fully capable, tested, and documented, HEC-PRM program will be ready for general public release in early 1993. The program would at that time meet HEC's high standards for publicly releasable programs, such as represented by the well-known HEC-1 and HEC-2 programs. Other applications and refinements are anticipated between now and general release in 1993.

CLIMATE-CHANGE APPLICATIONS

In the context used here, climate change refers to the long-term, fundamental shift in climate induced by permanent changes in contributing atmospheric and hydrometerological factors. Short-term or transient deviations from historical weather patterns that are explainable by usual random fluctuations are not considered. Climate change, should it occur, will therefore affect both the available water through changes to streamflow and society's requirements for water by altering use patterns. Studies of the water management impacts of climate change must address both these issues.

Should it be possible to represent anticipated climate-change effects with quantified, altered, expected streamflow and water demands, application of prescriptive models, such as HEC-PRM, could contribute insight into tradeoffs in water management policies. Alternative hydrologic monthly streamflow sequences would be prepared by adjusting historical period-of-record (or stochastic) streamflow for postulated climate-change effects, penalty functions altered to reflect postulated demand/value changes, and HEC-PRM executed. Results then would be compared for a wide array of hydrologic, water use, and value parameters, and conclusions drawn. If the results indicated that improved operation rules and policies would be desirable, further studies would be conducted to refine rule curves to reflect the postulated changes.

At present, climate-change studies are not part of the Missouri River Main Stem Master Water Control Manual Update studies. Current studies are based on evaluating alternative operation policies on the adjusted (to present) 92-year historical streamflow sequence. The potential for climate-change and possible streamflow-related impact continues to be debated by scientists. Far more definitive characterization of climate change than has been possible to date is required before system operation studies would be meaningful. At present, significant changes in use patterns and society preferences are the issues being addressed in studies to update operation policies. Nonetheless, operation policies and rules are revisited at regular intervals, about every 10 years, so that ample opportunity will exist to consider desired policy changes at such a future time as results of climate-change possibilities become more certain and quantified.

CONCLUSIONS

From the activities of Phase I, HEC staff conclude the following:

- Network flow programming is an appropriate tool for analysis of long-term system operation. It is simple enough to understand in theory, yet sophisticated enough to account for most critical system characteristics and operation requirements.
- A usable model (HEC-PRM) has been implemented.
- The success of a prescriptive model such as HEC-PRM depends on the capability of the penalty functions to capture the essence of operation goals and constraints.
- Additional development is required before the model and results will be available for distribution. The work under way will yield a model and penalty functions that will provide useful information for making decisions regarding long-term operation rules for the MRD system.
- Prescriptive models, such as HEC-PRM, have a role in study of water management impacts of possible climate change.

ACKNOWLEDGMENTS

This project was supported in part by the U.S. Army Corps of Engineers, Missouri River Division. The Corps' Institute for Water Resources developed the cost-based penalty functions. Bob Carl of HEC developed the trial model and performed the test applications. David T. Ford, Engineering Consultant, provided expert advice and assistance in model development.

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A METHODOLOGY TO ESTIMATE GLOBAL CLIMATE-CHANGE IMPACTS ON LAKE WATERS AND FISHERIES IN MINNESOTA

H.G. Stefan, J.G. Eaton, M. Hondzo,
B.E. Goodno, X. Fang, K.E.F. Hokanson, and J.H. McCormick

ABSTRACT

Minnesota's more than 10,000 lakes and many streams are the basis of a tourism industry that produces revenues on the same order as manufacturing or agriculture. Because of its latitude, Minnesota is expected to be heavily influenced by global warming. A doubling of atmospheric CO_2 will increase mean air temperature in Minnesota roughly by 4.5°C, according to the Columbia University Goddard Institute for Space Studies (GISS) general circulation model. This "greenhouse effect" projection will affect water temperatures, dissolved oxygen, and hence fish resources. An analysis of changes projected for the lakes of the state was conducted. The models, data bases, and assessment techniques employed can serve as templates for conducting analyses of impacts on other regions.

In Minnesota, a climate change associated with doubling of CO_2 would increase total good growth potential for all fish feeding in open water by 6 percent. The main beneficiaries would be warm-water fish (+ 53 percent) and cool-water fish (+ 20 percent). The main losers would be cold-water fish (- 41 percent). The impact of climate change on fisheries resources for the state of Minnesota is therefore estimated to be significant, at least in terms of distribution of guilds.

CONCEPT

Lake temperature stratification and dissolved oxygen (DO) simulation models have been developed and applied to lakes in Minnesota. The models are deterministic and calculate water temperature and DO as a function of depth on a daily time scale. The simulations are driven by weather input data from a 25-year period (1955-1979) to simulate past conditions, and are repeated with climate projected by the GISS general circulation model. Lake characteristics are specified in terms of surface area, maximum depth, area versus depth distribution, and Secchi depth as a surrogate for trophic status. For the oxygen simulations, oxygen demand and production-rate coefficients have to be specified as a function of trophic status.

A field data base of spatially and temporally corresponding water temperature and fish distribution information was used to specify thermal requirements for fresh-water fish. Maximum temperatures tolerated by individual species and temperature ranges for good growth were identified for three fish guilds, as were DO requirements. These criteria were applied to simulated thermal and DO conditions in lakes. It was thus determined which fish guilds could be present, and what growth potential existed or would exist after climate change.

Note: Participants Stefan, Hondzo, and Fang are on the staff of the University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Department of Civil and Mineral Engineering. Participants Eaton, Goodno, Hokanson, and McCormick are with the U.S. Environmental Protection Agency, Environmental Research Laboratory.

To estimate the response of fish in lakes of different characteristics, a lake data base for the state of Minnesota has been analyzed to identify 27 categories of lakes that cover the natural distributions of surface area, maximum depth, and Secchi depth in the state. Relative sensitivity of different classes of lakes to projected climate change has been determined and by integration, the impact of climate change on fish distribution and growth potential in the entire state has been estimated.

The conceptual interactions that were considered are indicated in Figure 1. The information flow used is detailed in Figure 2. Three major data bases were applied: (1) a fish-temperature data base management system (FTDMS), (2) a Minnesota lake fisheries data base (MLFD) and (3) weather data files from 1955-1979. The FTDMS was used to develop temperature criteria for fish. The lake data base and the weather data bases were applied in the deterministic, process-oriented models to simulate water temperature and dissolved oxygen structures. These results were then related to fish and temperature and DO requirements to determine fish presence and growth potential. This process was repeated for past climate and future climate parameter changes predicted by the GISS general circulation model. Details of this study can be found in a report by Stefan et al. (1991).

FISH THERMAL AND DISSOLVED OXYGEN REQUIREMENTS

Analysis of climate-change impacts on fish is based on a scheme that recognizes limits of thermal requirements for growth and survival of three fish guilds: cold-water, cool-water, and warm-water fish (Hokanson, 1990). The empirical model relating fish presence to water temperature is developed from stream data, but Hokanson et al. (1991) have proposed that the temperature regimen for a given thermal guild can also be used to describe the thermal niche within stratified water bodies. Forecasts were made of changes in thermal guilds rather than individual species because other requirements (such as available food and reproductive conditions, competitive or predatory relationships, etc.) are not generally well enough known or predictable for any given water body to determine the future presence of individual fish species.

The highest summer 95 percentile value (a weekly mean) for each species of thermal regime obtained from the FTDMS data base was selected as the maximum temperature value at which a fish species or guild would be present in a water body. This seemed appropriate in light of the wide geographical data distribution and the range of time scales over which measurements had been made. Table 1 gives the FTDMS distribution limit (maximum 95 percentile) temperatures for the three fish guilds. Further information on the FTDMS data base can be obtained from Hokanson et al. (1990).

TABLE 1
Thermal Criteria for Fish
(guild means and ranges for species within a guild)

Guild	Lower 50% Growth Limits	Upper Growth Criteria	Current FTDMS Max 95th Percentile	Optimum Temp
Cold-water	9.0 (6.4-11.8)	18.5 (15.5-21.2)	23.4 (22.1-26.6)	15.3 (11.5-18.7)
Cool-water	16.3 (13.2-18.2)	28.2 (27.8-28.8)	30.4 (28.0-32.3)	25.1 (24-25.7)
Warm-water	19.7 (17.7-22.5)	32.3 (31.4-34.7)	31.4 (28.7-33.6)	29.2 (27-32)

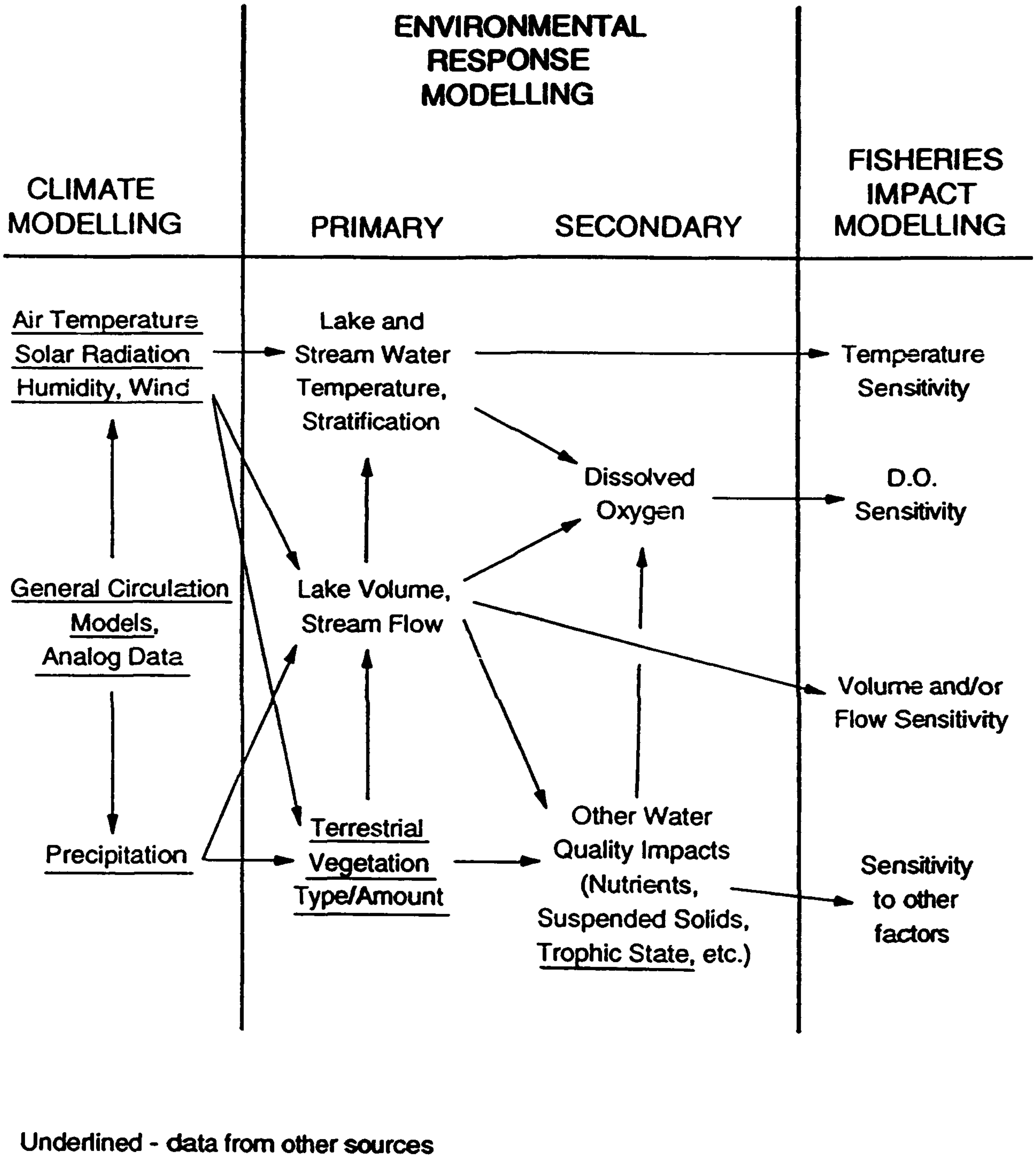
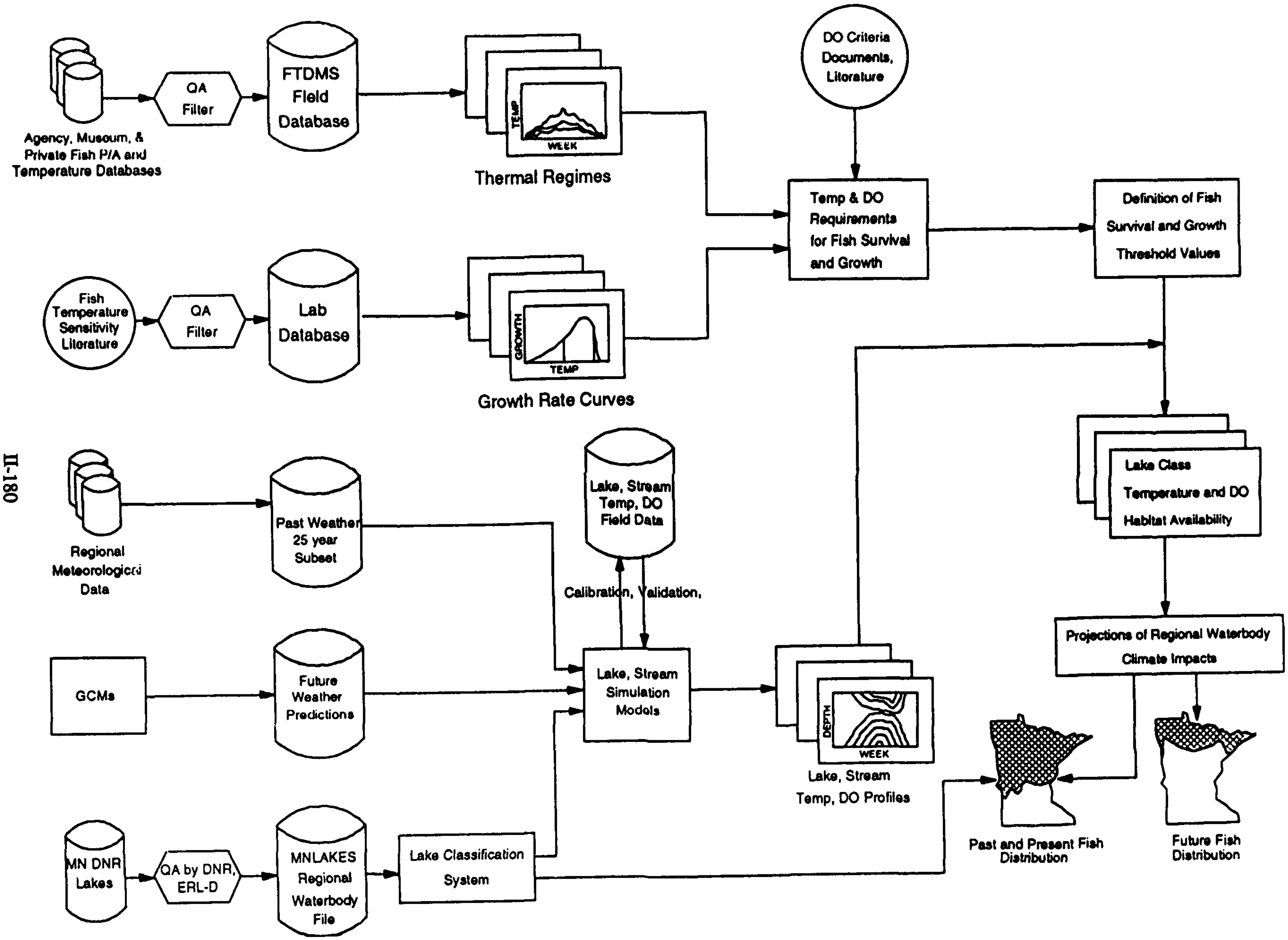


Figure 1. **Environmental response modelling.**


Agency, Museum, & Private Fish P/A and Temperature Databases
QA Filter
FTDMS Field Database
TEMP
WEEK
Thermal Regimes
Fish Temperature Sensitivity Literature
QA Filter
Lab Database
GROWTH
TEMP
Growth Rate Curves
DO Criteria Documents, Literature
Temp & DO Requirements for Fish Survival and Growth
Definition of Fish Survival and Growth Threshold Values
Lake Class Temperature and DO Habitat Availability
Projections of Regional Waterbody Climate Impacts
Regional Meteorological Data
Past Weather 25 year Subset
Lake, Stream Temp, DO Field Data
Calibration, Validation,
GCMs
Future Weather Predictions
Lake, Stream Simulation Models
DEPTH
WEEK
Lake, Stream Temp, DO Profiles
MN DNR Lakes
QA by DNR, ERL-D
MNLAKES Regional Waterbody File
Lake Classification System
Past and Present Fish Distribution
Future Fish Distribution

In addition to using the ability to survive as a gross measure of climate-change effect, a measure of growth potential was sought as a sub-lethal effect indicator. The arbitrarily chosen measure was the temperature range between that at which 50 percent of maximum growth occurred and the U.S. EPA (1976) maximum temperature for prolonged duration of exposure. This "good growth" temperature range could be calculated from growth rate experiments for several species in each guild, the values of which were averaged to obtain guild values. Since the amount of water volume and time spent within this range could be expected to contribute heavily to production of a fish population, a comparison of the volume*time product before and after climate change should be a useful measure of relative effects on growth potential. The lower and upper good growth temperature values used in this analysis are also shown in Table 1.

A second important aspect of the problem is the effect of climate change on dissolved oxygen. Not only do saturation values for DO vary with water temperature, but virtually all processes that add oxygen to water (reaeration, photosynthesis, etc.) or take dissolved oxygen out of the water (respiration, biochemical oxygen demand, etc.) are temperature dependent. Furthermore, dissolved oxygen distribution in a surface-water body depends strongly on mixing characteristics. In lakes, these mixing characteristics may be affected by weather changes such as wind.

Based on information in the EPA dissolved oxygen criteria document (Chapman, 1986), DO limits of 2.5 mg/l for warm-water fish and 3.0 mg/l for cool- and cold-water fish were selected. It was the intention to select values at which loss of populations would ultimately occur. The concentrations chosen are expected to result in significant mortality among individuals exposed for only a few days. In contrast, EPA criteria levels intended to protect these guilds are 4 and 5 mg/l, respectively.

By late summer, downward warming and upward deoxygenation of lakes can be so extensive that the thermal limit and the dissolved oxygen limit for presence of a fish guild may approach one another or overlap in major portions of the basin. The volume of suitable fish habitat is thus reduced or eliminated (see Figure 3).

TEMPERATURE AND DISSOLVED OXYGEN MODELING OF LAKES AND STREAMS

Model Concepts and Development

A one-dimensional, deterministic, unsteady lake water quality model, which has been applied successfully for several successfully years to simulate water quality in individual north-central U.S. lakes and for a variety of meteorological conditions (Ford and Stefan, 1980; Riley and Stefan, 1988; Gu and Stefan, 1990) was adapted to this study (Hondzo and Stefan, 1991b).

In the model, the lake is described by a system of horizontal layers, each of which is well mixed. Vertical transport of heat is described by a diffusion equation in which the vertical diffusion coefficient $K_z(z)$ is incorporated in a conservation equation for heat:

$$A\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(K_z A\frac{\partial T}{\partial z}\right)+\frac{H}{\rho_w c_p} \tag{1}$$

where T(z,t) is water temperature as a function of depth (z) and time (t), A(z) is the horizontal area of the lake as a function of depth, H(z,t) is the internal distribution of heat sources due to radiation absorption inside the water column, ρ_w is the water density, and c_p is the specific heat of water.

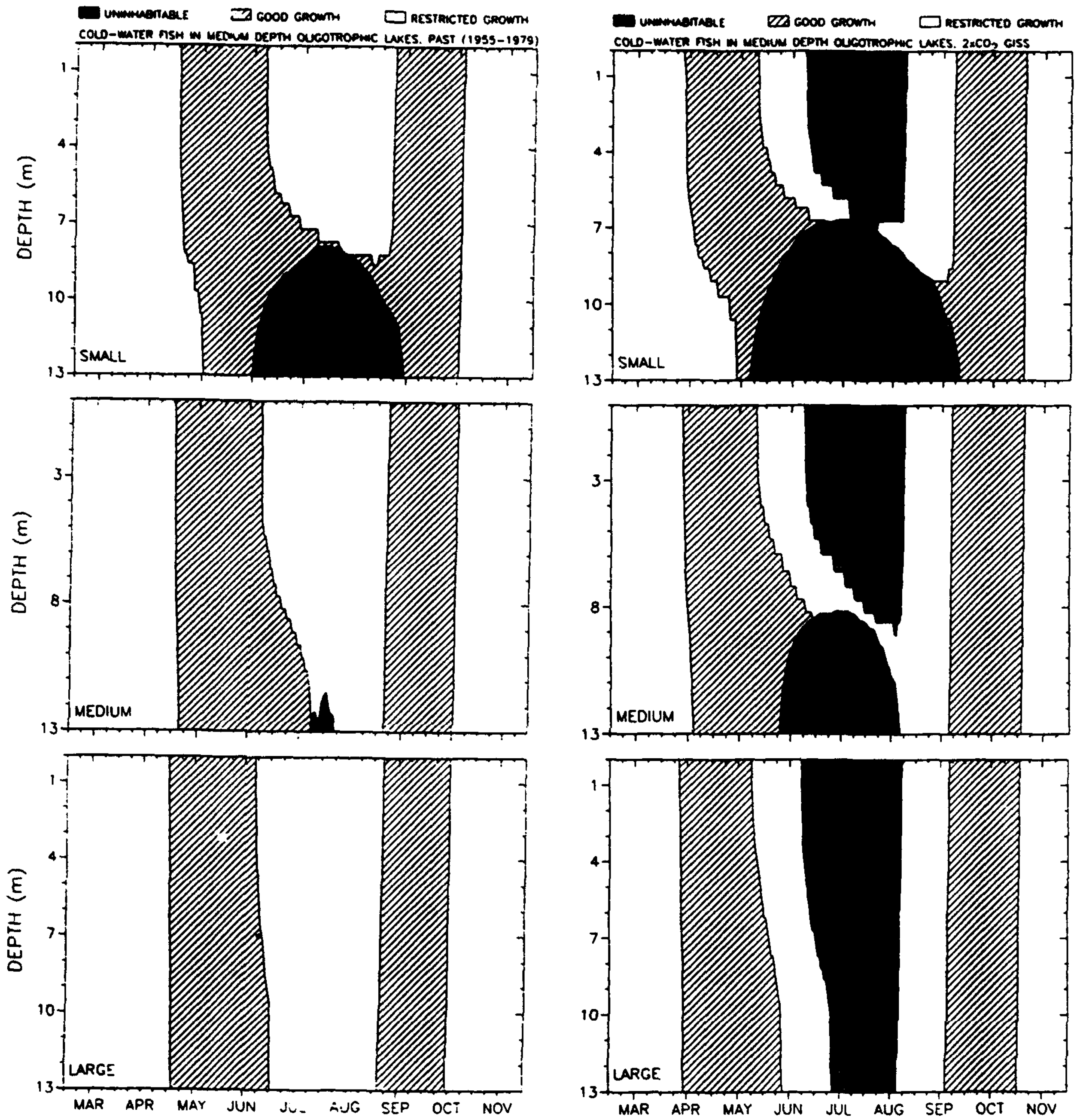


Figure 3. **Cold-water fish in medium depth oligotrophic lakes.**

The vertical temperature profile in the lake is computed from a balance between incoming heat from solar and long-wave radiation and the outflow of heat through convection, evaporation, and back radiation. The net increase in heat results in an increase in water temperature. The heat balance equation at the water surface is given by

$$H_n = H_{sn} + H_a + H_c + H_e + H_{br} \tag{2}$$

where H_n is net heat input at the water surface (kcal $m^{-2}day^{-1}$), H_{sn} is net solar (short wave) radiation, H_a is atmospheric long-wave radiation, H_c is conductive loss (sensible heat), H_e is evaporative loss (latent heat), and H_{br} is back radiation. The heat budget components in equation (2) are computed by empirical equations summarized by Ford and Stefan (1980). The vertical diffusion coefficient $K_z(z)$ is related to wind speed, lake area, and strength of stratification.

The DO model solves the one-dimensional (vertical), unsteady DO transport equation (3). Sedimentary oxygen demand (SOD), biochemical oxygen demand (BOD), as well as plant respiration are the oxygen sinks in the model, and rates are specified according to trophic status but variable with temperature. Reaeration and photosynthesis are the sources of oxygen in the model. Lake morphometry and daily weather parameters are model inputs. Lake trophic status is specified by chlorophyll-*a* concentration, BOD, and SOD.

$$\begin{aligned}\frac{\partial DO}{\partial t}-\frac{1}{A}\frac{\partial}{\partial z}(AK_z\frac{\partial DO}{\partial z})+\frac{1}{YCHO2}k_r\theta_r^{T-20}Chla\\ -P_{max}\theta_P^{T-20}\min\{L\}Chla+k_2\theta_{BOD}^{T-20}BOD\\ +\frac{S_b}{A}\frac{\partial A}{\partial Z}-k_L(DO_{sat}-DO)=0\end{aligned}$$

where

A = horizontal lake area (m^2)
BOD = concentration of BOD (mg l^{-1})
Chla = Chlorophyll concentration (mg l^{-1})
DO = dissolved oxygen concentration (mg l^{-1})
DO_{sat} = saturation oxygen concentration (mg l^{-1})
k_L = oxygen exchange coefficient in the surface layer (day^{-1})
K_z = vertical eddy diffusivity ($m^2 day^{-1}$)
k_r = respiration rate coefficient (day^{-1})
k_2 = organic decomposition rate (day^{-1})
min[L] = light limitation for growth
P_{max} = maximum specific rate of photosynthesis (mg O_2 mg $Chla^{-1}$ 1)
S_b = sediment oxygen demand coefficient (gO_2 m^{-2} day^{-1})
T = temperature (°C)
YCHO2 = ratio of mg chlorophyll per mg oxygen in photosynthesis and respiration
θ_r, θ_{BOD}, θ_P = temperature coefficients for respiration, BOD, and photosynthesis, respectively

Model Input Requirements

The lake models are applied in daily time steps with input of mean daily values for meteorological variables. Weather data files were assembled for three main weather stations (Minneapolis-St. Paul and Duluth, Minnesota; and Fargo, North Dakota) for a 25-year period (1955 to 1979). A climate-warming trend already existed in the 1980s (Jones et al., 1986; Kerr, 1989).

Secchi depth is an open-water average value (May to November). Relationships between Secchi depth, total phosphorus, and mean summer chlorophyll-*a* levels in Minnesota lakes have been developed by Heiskary and Wilson (1988). Simulations started with isothermal conditions (4°C) on March 1 and progressed in daily time steps until November 30. Ice goes out of Minnesota lakes sometime between the end of March and the middle of May (Kuehnast et al., 1982). With climate change, this date may advance by as much as a month. To allow for these variable conditions, a 4°C isothermal condition was maintained in the lake water temperature simulations until simulated water temperatures began to rise above 4°C. This method permitted the model to find its own date of spring overturn (4°C) and the simulated summer heating cycle and stratification started from that date.

Model Calibrations and Validations

Model coefficients were kept at their initially specified value throughout the entire simulation period. Examples of model validation are given by Hondzo and Stefan (1991b). The lake model simulates onset of stratification, mixed layer depth, and water temperature well. Standard error between seasonally measured and simulated water temperatures in seven lakes used for validation was 1°C. This is mostly due to small differences in predicted thermocline depth.

The DO model for lakes was calibrated and validated with measurements by R. Osgood (1984, 1985) in seven Twin Cities metropolitan area lakes. The main calibration parameter was SOD uptake, which was a function of trophic status. Standard errors for calibration ranged from 0.6 to 2.3 mg/l with an average of 1.4 mg/l. The main cause of errors in the DO predictions was small deviations in mixed layer depths (1 m or less) where the DO profile has very large gradients.

Future Climate Scenarios

Projected future long-term (25-year) average lake temperatures were calculated after applying increments to the historical weather parameters. The increments were monthly additive or multiplicative values for air temperature, wind speed, relative humidity, and other weather parameters. Numerical values taken from the nearest GCM grid point are shown in Table 2. The monthly incremental values were obtained from NOAA, and were derived from the outputs of the GISS general circulation model for doubling of CO_2 in the atmosphere (Hansen et al., 1983).

REGIONAL CLIMATE-CHANGE IMPACT ANALYSIS

Minnesota Lake Fisheries Database

The Minnesota Department of Natural Resources has developed a Minnesota Lake Fisheries Database (MLFD), which contains fisheries survey and physical and chemical parameter information for 3,002 Minnesota lakes. A statistical analysis of the Minnesota lakes in the MLFD led to frequency distributions that were then used

TABLE 2
Climate Parameter Changes (GISS)
at Minneapolis-St. Paul

	Range	Average
Air Temperature (°C)	+2.1 to +7.0	+4.5
Solar Radiation (%)	-2 to +12	+2.3
Wind Speed (%)	-53 to +500	
Relative Humidity (%)	-10 to +13	0
Precipitation (%)	-30 to +28	-2

to classify the lakes into three ranges of surface area, maximum depth, and Secchi depth, as shown in Table 3. These represent conditions in 27 classes of lakes. The number of lakes in each class is shown in Table 4.

Climate-Change Impact on Lake Water Temperature and DO

Regional simulations were made (separately for southern and northern Minnesota) for the 27 classes of lakes. Hondzo and Stefan (1991a) describe the results of the water temperature simulations for southern Minnesota in detail. Main findings are as follows.

Simulated epilimnetic temperatures are found to be predominantly related to weather and secondarily to lake morphometry. Epilimnetic temperatures are raised by climate change for all lake classes, in the average by 3°C, compared to 4.5°C air temperature increase by the climate change. Maximum daily differences in water temperatures of 7.2°C and 4.9°C are calculated in April and September. The seasonal maxima of epilimnetic temperatures are raised only by 2.0°C with climate change.

Hypolimnetic temperatures are strongly influenced by lake morphometry, mixing events in spring, and only secondarily by summer weather phenomena (see Figure 4). The highest hypolimnetic water temperatures are calculated for large, shallow, eutrophic lakes. After climate change, hypolimnetic water temperatures are as follows: shallow lakes, warmer on average by 3.1°C; large-area medium-depth lakes, warmer by 2.0°C; and deep lakes, cooler on average by 1.1°C.

With climate change, lakes stratify earlier, and overturn later in the season. Length of the seasonal stratification period is increased by 40 to 60 days. Simulated mixed-layer depths decrease in the spring and summer, and increase in the fall.

The regional DO model and its results are described by Stefan and Fang (1991). The DO model simulation results showed great sensitivity to sedimentary oxygen demand and vertical mixing. In deep lakes that are dimictic, the DO distribution is much different from shallow lakes. Hypolimnetic oxygen depletion in deep lakes can be substantial. Some deterioration of DOs with climate change is noticeable near the lake bottom. Periods of DO depletion are longer and water volumes that are depleted of DO become larger after climate change.

TABLE 3
Ranges of Physical Lake Parameters
Used to Describe 27 Minnesota Lake Classes

Lake Key Parameter	Range	Cumulative Frequency	Represent Value Used	Descriptive Term
Maximum Depth (m)	< 5	lower 30%	4	shallow
	5 - 20	central 60%	13	medium
	> 20	upper 10%	24	deep
Area (km^2)	< 0.4	lower 30%	0.2	small
	0.4 - 5	central 60%	1.7	medium
	> 5	upper 10%	10	large
Secchi Depth (m)	< 1.8	lower 20-50%	1.2	eutrophic
	1.8 - 4.5	central 20-50%	2.5	mesotrophic
	> 4.5	upper 0-10%	4.5	oligotrophic

Application of Fish Temperature and DO Requirements to Lake Temperatures and Dissolved Oxygen

Fish survival and growth temperature criteria were applied to simulated water temperatures and DO. Figure 3 shows schematically how this was done. Three isotherms were singled out for each fish guild: the survival temperature, the upper good growth temperature limit, and the lower good growth temperature limit, respectively. Similarly, the isopleth that designates the critical DO survival value is shown. Between these lines, three habitats can be identified: (1) uninhabitable space when temperature is above or DO is below the artificial limit; (2) good growth habitat if temperature is between the upper and lower growth limits and DO is above the critical limit; and (3) restricted growth habitat if temperature is above the upper good growth limit but below the survival limit, if temperature is below the lower good growth limit, and if DO is above critical.

In Figure 3, simulated past and future habitat distributions are presented side by side. Habitat areas are plotted against depth and time, and represent 25-year average values.

Climate-Change Impact on Fish

A fish guild will be absent from a lake if at all depths there is either a temperature or DO survival limitation, so that no habitat is left (see Figure 3, right bottom). If the period of time during which conditions everywhere in the lake become unsuitable for fish because either temperature is too high or DO is too low for more than 7 days, survival of fish was considered impossible. Growth potential can be assessed by (1) the length of the good growth season and (2) the partial lake volume integrated over time suitable for good growth. Changes, due to climate change, of the numerical values of these parameters were obtained and indicate the following:

(1) *Cold-water fish* currently have only a remote chance to survive southern Minnesota summers, and only in lakes that are both large and deep, which is rare in southern Minnesota. In future climate scenarios, conditions for cold-water fish worsen according to the simulation results, and potential for cold-water fish survival in southern Minnesota lakes becomes zero. In northern Minnesota, lake temperatures and DO conditions are presently suitable for cold-water fish in all classes of lakes. After climate change, a substantial reduction in cold-water fish habitat

Table 4.

Total Water Volume Integral over Time (Billion m^3*Day) for Good Growth in All Minnesota Lakes (3002 Lakes)

LAKE CHARACTERISTICS				FISH GUILD								
MAX. DEPTH	SURF. AREA	TROPH. STAT.	NUMB. LAKES	COLD			COOL			WARM		
				PAST	GISS	DIFF	PAST	GISS	DIFF	PAST	GISS	DIFF
S	S	E	229	5.4		-5.4	7.6	9.5	1.9	4.6	8.0	3.3
S	S	M	199	5.3		-5.3	6.6	8.4	1.8	3.8	7.1	3.3
S	S	O	3	0.06		-0.06	0.2	0.1	-0.1	0.1	0.1	0.0
S	M	E	321	35.4		-35.4	96.2	113.4	17.2	67.3	102.4	35.1
S	M	M	124	23.8		-23.8	34.5	43.0	8.5	21.5	37.6	16.1
S	M	O	4	0.5		-0.5	1.2	1.4	0.2	0.9	1.3	0.5
S	L	E	26	9.0		-9.0	43.9	52.0	8.1	32.9	48.1	15.2
S	L	M	5	3.7		-3.7	7.7	9.4	1.7	5.2	8.5	3.2
S	L	O	0	0		0	0	0	0	0	0	0
M	S	E	167	7.7	4.5	-3.1	12.5	13.2	0.7	7.8	10.5	2.7
M	S	M	422	32.9		-32.9	34.7	41.7	7.0	20.7	32.2	11.5
M	S	O	84	7.5		-7.5	7.9	10.1	2.1	4.8	7.8	3.0
M	M	E	244	80.2	57.4	-22.9	194.	208.	14.0	130.	168.	38.8
M	M	M	633	421.5	360.9	-60.6	487.	586.	98.9	292.	452.	160.
M	M	O	83	58.8	59.5	0.6	68.1	85.8	17.8	41.5	66.8	25.3
M	L	E	31	58.6		-58.6	153.	179.	26.0	107.	148.	41.6
M	L	M	50	184.8		-184.	224.	283.	59.3	138.	222.	83.9
M	L	O	1	3.6		-3.6	3.9	5.2	1.3	2.4	4.0	1.6
D	S	E	7	0.8		-0.8	0.6	0.6	0.0	0.3	0.4	0.1
D	S	M	33	3.9	2.1	-1.77	3.4	4.1	0.6	1.9	2.9	1.0
D	S	O	26	4.7	2.9	-1.80	3.1	4.2	1.1	1.6	2.9	1.3
D	M	E	13	4.1		-4.15	13.9	13.7	-0.2	9.3	10.7	1.3
D	M	M	137	157.5	81.1	-76.4	141.	163.	22.0	78.9	117.1	38.2
D	M	O	74	123.0	75.0	-47.9	82.5	109.	26.6	43.0	75.4	32.4
D	L	E	10	76.8	26.0	-50.9	76.9	83.4	6.5	48.5	63.8	15.3
D	L	M	59	499.3	319.1	-180.	425.	515.	90.0	221.	368.	147.
D	L	O	17	146.5	117.8	-28.7	126.	167.	41.0	65.4	117.	51.6
SUM =			3002	1956	1106	-850	2258	2711	453	1350	2086	736

SHADED BOXES INDICATE UNINHABITABLE CONDITIONS

MAXIMUM DEPTH:
S = SHALLOW (4 m)
M = MEDIUM (13 m)
D = DEEP (24 m)

SURFACE AREA:
S = SMALL (0.2 km^2)
M = MEDIUM (1.7 km^2)
L = LARGE (10 km^2)

TROPHIC STATUS:
E = EUTROPHIC
M = MESOTROPHIC
O = OLIGOTROPHIC

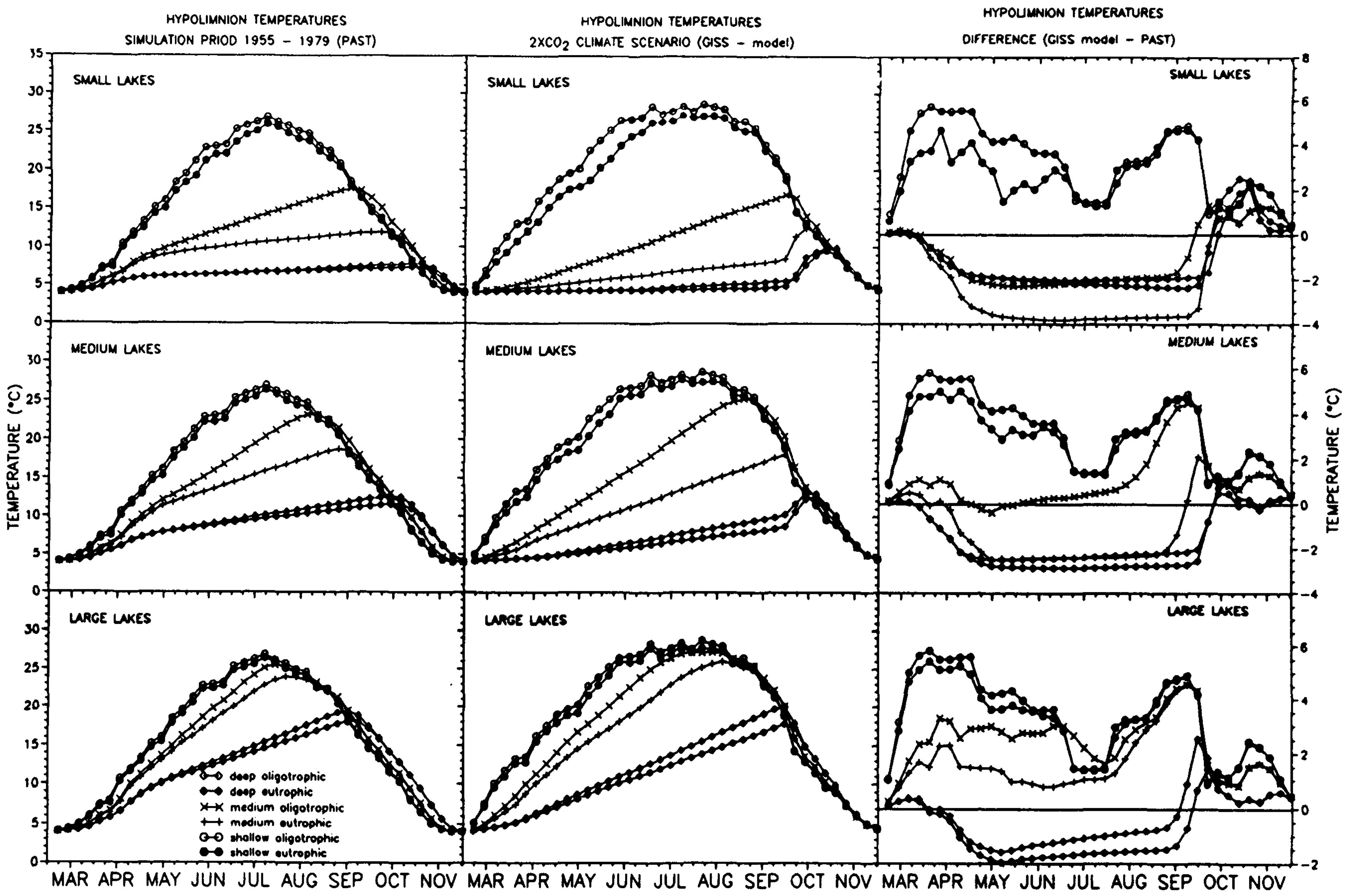


Figure 4. Hypolimnion temperature

is predicted. Shallow lakes and large lakes of medium depth will no longer support cold-water fish. The length of the good growth season for cold-water fish in northern Minnesota lakes will increase in deep oligotrophic lakes and decrease or remain the same in deep eutrophic lakes. It will decrease slightly in lakes of medium depth and size.

(2) *Cool-water fish* find good growth conditions in the epilimnetic waters of all deep stratified lakes, and also in the shallow polymictic lakes of southern Minnesota. Growth potential based on temperature and DO is better for cool-water fish than warm- or cold-water fish in southern Minnesota lakes. Climate change will lengthen the total good growth season between 26 and 40 days. It is presently between 131 and 137 days long. Time-integrated volumes of good growth habitat for cool-water fish in southern Minnesota lakes will increase by no more than 16 percent for any class of lake. Changes will be the largest in lakes that are well mixed; i.e., in shallow lakes and large lakes of medium depths.

Cool-water fish presently also find habitat in all northern Minnesota lakes. The length of the good growth season in the north is, however, from 29 to 42 days shorter than in the south. After climate change, it will be lengthened by 29 to 41 days; i.e., it will become in the north as it is presently in the south. Time-integrated good growth volumes will increase 9 to 35 percent depending on lake class.

(3) *Warm-water fish* currently find good growth conditions in the surface (epilimnetic) waters of southern Minnesota lakes but have to contend with a smaller volume of good growth habitat and a shorter season than the cool-water fish. Warm-water fish are frequent in southern Minnesota lakes. After climate change, the simulated good growth volumes are more or less unchanged, but more confined to the surface waters. The good growth season will increase by 31 to 42 days from the present 103 to 108 days. Time-integrated growth volume will rise between 9 and 40 percent; the largest increase (31 to 40 percent) will be for the shallow lakes, and the smallest (9 to 21 percent) for the deep lakes.

Warm-water fish have a short season for good growth (from only 55 to 62 days in northern Minnesota lakes). After climate change, the good growth season length will become 102 to 111 days. This is nearly identical to the present conditions in southern Minnesota lakes. Time-integrated volumes for good growth of warm-water fish will increase dramatically by 66 to 92 percent in northern Minnesota lakes.

Lake depth, lake size, and trophic status are the three lake parameters that were used as independent variables and their effects on simulation results and fish projections can be summarized as follows:

(1) *Lake depth*. The losses or gains in good growth potential due to global climate change are larger in deep lakes than in shallow ones.

(2) *Lake size*. In shallow lakes that are usually well mixed or in polymictic lakes, good growth potential decreases slightly (order of 10 percent) as lake surface area increases. For deep lakes that are usually stratified, the trend is opposite and more pronounced. After climate change, this trend is maintained, although weakened.

(3) *Trophic status*. The effect of trophic status on fish in shallow lakes is small. In deep lakes, which have a seasonal stratification and are dimictic, oligotrophy is usually associated with higher growth potential. This trend continues after climate change. The largest losses in good growth volume due to climate change appear to occur in eutrophic lakes (for cold-water fish); the largest gains (for cool- and warm-water fish) are projected to occur in oligotrophic lakes of otherwise same size and depth.

The *total statewide impact of climate change on fish* is determined from the parameters for each of the 27 lake classes. These parameters are multiplied by the relative frequency of lakes in each class. The total number of lakes in the lake data base used is 771 for southern Minnesota and 2,231 for northern Minnesota. The total lake volumes are 5.6 and 18.7 billion m^3 in southern and northern Minnesota, respectively, for a total of 24.3 billion m^3. Surface areas are 1.42 and 3.58 billion m^2, respectively, for a total of 5.0 billion m^2.

The total water volumes in which good growth is possible are given by lake classes and fish guilds in Table 4 for the state as a whole for past and future climates. A summary for all 3,002 lakes in the state lake data base is given in Table 5. The interpretation is as follows:

(1) In northern Minnesota lakes where cold-water fish find suitable summer habitat, a major loss of good growth habitat volume (41 percent) is projected.

(2) *Cool-water fish* have done well in Minnesota lakes under *average* climate conditions of the past (1955 to 1979). Under the future climate of the 2 X CO_2 GISS scenario, the time-integrated water volume in which good growth of cool-water fish is possible will increase by 20 percent for the state as a whole. The increase will be more in the north (25 percent) than in the south (8 percent).

(3) The time-integrated good growth potential for warm-water fish will increase by 53 percent for the entire state; much more in the north (71 percent) than in the south (21 percent). Under past climate conditions, the total time-integrated good growth potential for warm-water fish was 60 percent of that for cool-water fish. After climate change, it will be 77 percent.

MANAGEMENT IMPLICATIONS

Evaporation from lakes was found to be increased by about 300 mm by climate change, making the total evaporative loss about 1,200 mm. Water temperature and dissolved oxygen were simulated with the assumption that lake stages would remain unchanged. If minor (± 1m) changes in lake stages do occur, the results of this study will not be dramatically changed. If larger changes must be anticipated, interpolations between the simulation results provided herein for lakes of different depths and surface areas can provide a new estimate of impacts on fish. A complete study of lake water budgets before and after climate change is still needed.

Table 5.

Summary of Survival (% Lake Volume), Good Growth Season Length (Days), and Good Growth Time*Volume (Billion m^3*Day) for 3002 Minnesota Lakes

PARAMETERS	FISH GUILD											
	COLD			COOL			WARM			ALL FISH		
	PAST	GISS	DIFF	PAST	GISS	DIFF	PAST	GISS	DIFF	PAST	GISS	DIFF
SURVIVAL (%)	81	60.7	-20.2	100	100	0	100	100	0			
GOOD GROWTH SEASON (days)	143	161	18	107	142	35	70	113	43			
GOOD GROWTH VOLUME * TIME (Billion m3*day)	1956	1106	-850	2258	2711	453	1350	2086	736	5564	5903	339

Overall, climate change will increase the good growth potential of cool- and warm-water fish in most Minnesota lakes and reduce the good growth potential for cold-water fish in many Minnesota lakes. For all of Minnesota, the time-integrated lake volumes for good growth prior to climate change were calculated to be roughly in proportions of 9:10:6 for cold-, cool-, and warm-water fish, respectively. After climate change, the proportions are projected to be 5:12:9. The total good growth potential for fish is increased by 6 percent by climate change. Most of that increase is in the north.

The main factor that limits lake volume for good growth of cool-water fish is lack of dissolved oxygen. Artificial aeration of lake metalimnia without destruction of the thermocline has the potential to increase cool-water fish growth potential after climate warming, but may be economically applicable only to selected lakes.

In shallow lakes, trophic state seems fairly inconsequential for growth potential changes. Therefore current effects to curb cultural eutrophication of such lakes in Minnesota will have a relatively minor effect on the consequences of global climate change for fish. In lakes with seasonal stratification, oligotrophic conditions result in smaller losses of good growth volumes for cold-water fish and larger gains of good growth volumes for cool-water and warm-water fish. Therefore, curbing cultural eutrophication of deep lakes will be beneficial before and after climate change.

There will be more fish production potential in Minnesota lakes after climate change than before, but cold-water fisheries will be replaced in part by warm-water fish. Sports fishermen will need to be prepared for this change.

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THE SENSITIVITY OF WATER RESOURCES MANAGEMENT TO CLIMATE CHANGE: A GREAT LAKES CASE STUDY

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ABSTRACT

The availability of adequate fresh-water supplies is potentially one of the country's most serious long-range problems. The Great Lakes contain about 95 percent of the United States' fresh surface-water supplies and 20 percent of the world's fresh surface-water supplies. These water resources serve many uses including hydropower, industrial, navigation, municipal, recreation, and fish and wildlife habitat. Two of the Great Lakes, Superior and Ontario, are currently regulated for water resources management. Present water management strategies are based upon the natural water supply and resulting water-level fluctuations over the past 100 years. Recent studies, using general circulation model outputs coupled with hydrologic simulation models, indicate a 23 to 51 percent reduction in net basin water supplies to the lakes. Potential lake-level changes range from -0.4 m for Lake Superior to as much as -2.5 m on Lakes Michigan and Huron. These results have major environmental and socioeconomic implications and will require new paradigms in water resources management. Additional demands for Great Lakes water from outside the basin will also likely intensify. Policies will have to be developed to adequately address water allocation conflicts as well as to protect the quality and quantity of future water supplies.

INTRODUCTION

The Great Lakes system (see Figure 1), is one of the world's major water resources. It contains approximately 23,000 km^3 of water, representing 95 percent of the United States' and 20 percent of the world's fresh surface water. They are also one of the most intensively used fresh-water systems in the world, serving multiple interests including navigation, hydropower, recreation, and riparian. Some significant uses of the Great Lakes have become dependent upon their small variation in water levels, resulting in system sensitivity to even small changes in the lake levels. Climate change, represented by global warming or cooling, could have a significant effect on the Great Lakes and the surrounding region. Because of their large surface areas and constricted connecting channels, the Great Lakes filter out much of the annual variability and react primarily to the longer period fluctuations such as those represented by climate change.

Examples of the regional response to climate change are demonstrated by the northern hemisphere warming and cooling trends during this century. The warming over the northern hemisphere between the 1920s and the 1960s is well documented in the records of the Great Lakes. The mid-century northern hemisphere cooling trend is also reflected in the Great Lakes region. The annual mean of the air temperatures around the Great Lakes for the period 1960 to 1980 is 0.8°C cooler than the prior 30-year period. The precipitation from 1966 to 1986 was extremely high with very little variability. For the upper Great Lakes 17 out 21 years of this period had above-average precipitation. The cooling trend combined with the high precipitation regime to give exceptionally high water supplies to the basin. The mid-1980s brought record-high lake levels, flooding in low-lying areas, and extreme erosion damages along the lakeshore bluffs.

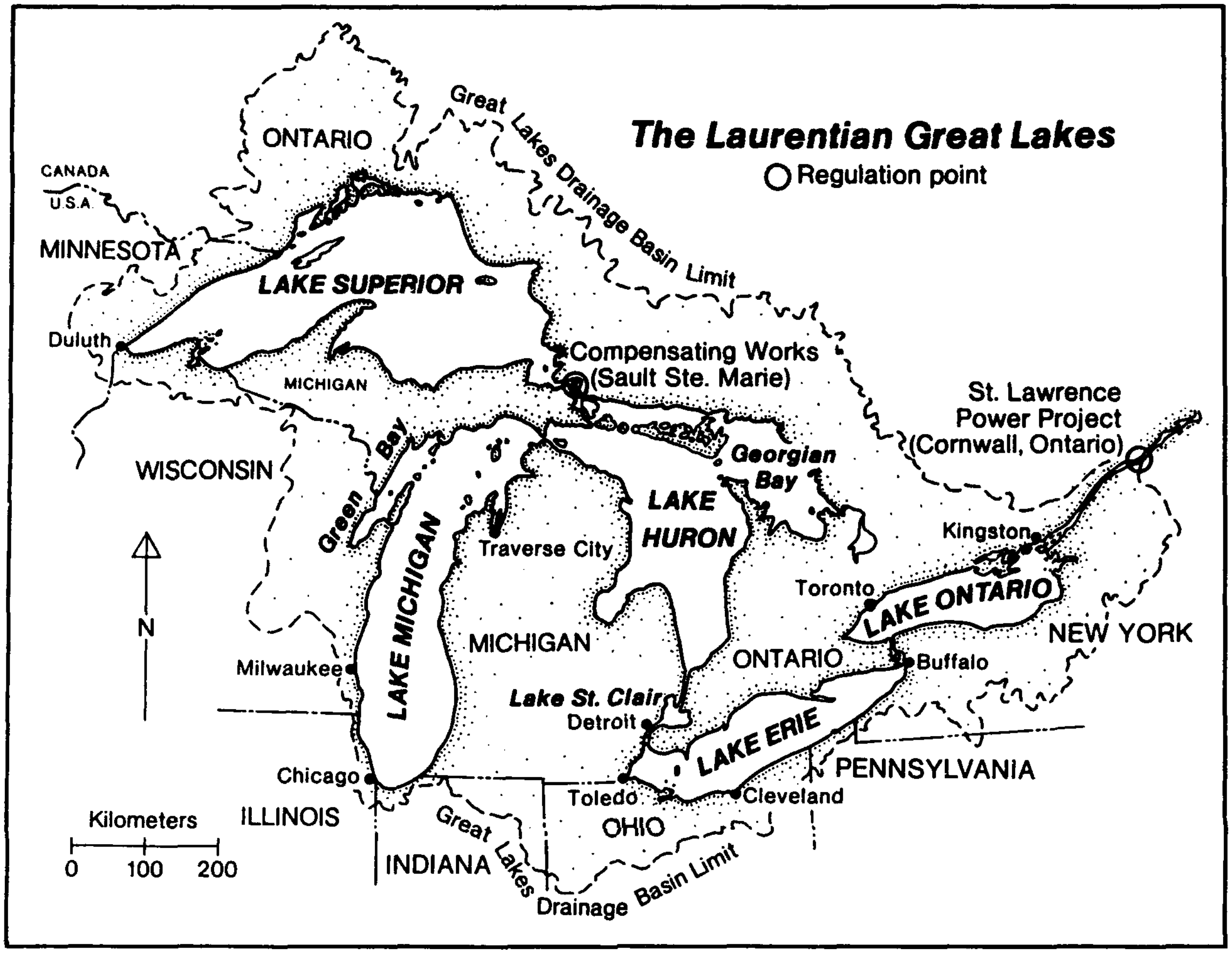

Figure 1. **The Laurentian Great Lakes.**

The current concern is that climate warming, resulting from increases of greenhouse and other gases, could result in major changes to the hydrologic cycle and water resources of the Great Lakes. Estimates indicate a temperature rise of between 3°C and 7°C might be expected over the Great Lakes region. In addition, changes in the amount and seasonal distribution of precipitation would likely occur. The basin has not been widely affected by drought for an extended period in the past 50 years. This could likely change as a result of the scenarios possible in the future. The importance of potential climate warming on the water resources of the Great Lakes has been recognized for the past decade (Quinn and Croley, 1983; Quinn, 1987; Cohen, 1986, 1987; Hartmann, 1990; Croley, 1990). This assessment uses the data from Croley (1990) and Hartmann (1991) to examine the sensitivity of Great Lakes water resources to potential climate change.

CLIMATE SCENARIOS

There are several methods that can be used to examine the potential impacts of climate change upon the water resources of the Great Lakes basin, including climate analogues, climate transposition, and general circulation models. This study uses the output of three general circulation models, the Oregon State University (OSU) model, the Goddard Institute for Space Studies (GISS) model, and the Geophysical Fluid Dynamics Laboratory (GFDL) model, used in the Environmental Protection Agency's Report to Congress on the potential effects of global climate change on the United States (U.S. EPA, 1989). The results of the changes in the basin temperature and precipitation used to drive the hydrologic models for an equivalent doubling of CO_2 are given in Table 1. Additional detailed information is available from Croley (1990).

It should be noted that many GCM output variables have a high degree of uncertainty associated with them. For example, the Great Lakes have a major impact on the climate of the basin while the GCMs do not recognize the existence of the lakes due to their large spatial scales. This can affect seasonal temperature distribution, snowfall, humidity, and wind speed. The GCM outputs do, however, provide data for examining the potential sensitivity of the system.

IMPACTS ON WATER SUPPLIES AND LAKE LEVELS

The general circulation models' meteorological outputs are used to drive a series of hydrologic models to estimate the hydrologic system response in terms of soil moisture, runoff, evapotranspiration, and evaporation from the lake surface. The sum of the precipitation and runoff minus the evaporation yields the net basin water supply to the system. The water supplies are then input into a hydrologic response model (Quinn, 1978), including the existing regulation plans for Lakes Superior and Ontario, to provide the lake level and connecting channel responses to the climate-change scenarios. The overall water supply data are given in Table 2 and the resulting lake levels are given in Table 3. Additional information is available from Hartmann (1990). The Lake Ontario regulation plan failed under all scenarios while the Lake Superior regulation plan failed under the GFDL scenario.

The Great Lakes have historically enjoyed a relatively small range in lake levels, approximately 1 m from the average annual maximum to the average annual minimum. Superimposed upon the average levels are seasonal cycles of 40 cm to 45 cm. Thus, the probable impacts of climate warming of decreasing the water supplies through increased evapotranspiration from the land surface resulting in smaller runoff into the lakes, of increasing the evaporation from the lake surfaces, and finally by any changes in precipitation patterns will result in lake levels much lower than those recorded over the past 150 years. These changes would have a major impact on the water resources management of the system.

TABLE 1
Differences in Meteorological Variables for a Doubling of CO_2*

Basin	Air Temperature (°C)			Precipitation (mm)		
	GISS	GFDL	OSU	GISS	GFDL	OSU
Superior	4.3	7.2	3.4	148	-36	58
Michigan	4.7	6.2	3.5	16	-8	42
Huron	4.6	6.4	3.3	-43	28	46
Erie	4.7	5.7	3.4	-53	48	54
Ontario	4.6	5.9	3.2	-66	27	74

*Mean of three GCMs (Croley, 1990)

TABLE 2
Percentage Change in Water Supply Variables Resulting From a Doubling of CO_2*

Scenario	Basin Runoff	Over-Lake Precipitation	Over-Lake Evaporation	Net Basin Supply
GISS	-24	+4	+27	-37
GFDL	-23	+0	+44	-51
OSU	-11	+6	+26	-23

*From Croley (1990)

TABLE 3
Changes in Lake Levels Due to a Doubling of CO_2*

Lake	Lake Level (m)		
	GISS	GFDL	OSU
Superior	-0.46	-**	-0.47
Michigan-Huron	-1.31	-2.48	-0.99
Erie	-1.16	-1.91	-0.79

*From Hartmann (1990)

**Lake Superior regulation plan failed

WATER RESOURCES IMPACTS AND MANAGEMENT IMPLICATIONS

The decreased water supplies and lake levels would have major impacts on navigation, hydropower, fisheries, recreational boating, and the ecosystem. The Great Lakes/St. Lawrence Seaway is a major fresh-water transportation system. This system depends upon adequate depths in the connecting channels and harbors to function at full capacity. Under the climate-warming scenario, channel depths would decrease by 0.5 m to 2.5 m, necessitating extensive dredging in both the connecting channels and the major harbors. Much of this area has not been dredged in the past 20 years. In a number of areas the dredged material is highly contaminated, creating a problem with spoil disposal. On the other hand a decreased ice season could lead to an extension of the current navigation season, contributing to better vessel utilization and a decrease in stockpiling.

The waters of the Great Lakes are extensively used for hydropower production. Facilities range from low head plants in the St. Mary's River to high head facilities in the Niagara and St. Lawrence rivers. A climate warming would result in decreased flows and water surface elevations that would contribute to lower hydropower production. This could be important, as hydropower is cheap and nonpolluting when compared to its primary alternative, fossil fuel. Fossil fuel and nuclear power plants sited around the lakes use lake water for cooling. A climate warming could produce increased consumptive use of water, which would further exacerbate the anticipated low lake levels.

The Great Lakes system contains one of the nation's prime sports fisheries, as well as a smaller commercial fishery, representing billions of dollars to the economy. A climate warming could result in a change in the species composition of the fishery with cooler water species giving way to warmer water species. This could have a significant impact on the value of the fishery. As an example, whitefish, a valuable commercial species, apparently depends upon an ice cover for adequate spawning and survival. Climate change could drastically reduce the ice cover in prime spawning areas.

The Great Lake system is one of the prime recreational boating areas in the country. The three-county area around Detroit has more boating registrations than any other area in the United States. The lower lake and connecting channel water levels resulting from climate change would greatly reduce the areas currently accessible to small craft, including the small passenger vessels that are operating in many areas at the present time. This could require extensive private dredging and the rebuilding of ramps.

Finally, a long-term climate warming would adversely affect the valuable Great Lakes ecosystem. Currently existing wetlands would be eliminated, and the diversity of species would probably be decreased. The complex food web would also be disrupted with a major change in species composition. Decreased water supplies would also impact water quality by increasing the flushing times for the lakes and perhaps contributing to the oxygen depletion in Lake Erie. The changed climate could also induce circulation changes affecting sediment, biological, and contaminant transport. Changes to the pelagic and near-shore ecosystem dynamics and species composition could also be expected.

The debate over inter-basin diversion of water into and out of the Great Lakes is also likely to intensify. There will be demands to increase the amount of water diverted into Lake Superior through existing diversions as well as new potential diversions. At the same time, efforts will likely be taken to divert additional water into the Mississippi River basin. Simultaneously, the Great Lakes response would likely be to curtail the water diverted out of Lake Michigan at Chicago.

The Great Lakes are a shared resource between the United States and Canada. There are also numerous state, provincial, county, and municipal jurisdictions leading to a complex jurisdictional structure. This will require a coordinated approach to policy development for coping with lowered lake levels. The policy implications of long-term lowered lake levels are far different than the major policy deliberations during the past several years, which have emphasized coping with high lake levels. Many riparians around the lake consider the current near-average lake levels to represent low conditions. Extensive revision of the existing regulation plans as well as the possible regulation of Lake Michigan-Huron and Lake Erie will likely be required to maintain lake levels at desirable levels. This will result in low flows in the connecting channels and in the St. Lawrence River. Major policy decisions will have to address the distribution of benefits between commercial, riparian, recreational, and ecological interests; between upstream and downstream interests; and finally between the many jurisdictional interests.

CONCLUSIONS

Global warming will likely have severe implications for the Great Lakes water resources. There will be inadequate water supplies to maintain the historical water level and flow regimes. The decreased lake levels of 0.5 m to 2.5 m will require major adaptation by all interests as well as lead to increased regulation of the system. The changes will require a new paradigm of how the lakes will be viewed from social, economic, and ecological perspectives. New policies will have to be developed and implemented to balance the competing interests. Additional studies should be undertaken as refined general circulation models with better spatial resolution become available. The next stage of climate-change studies on the Great Lakes should include mesoscale atmospheric models embedded in the general circulation models. This will enable the analysis of lake-related effects and responses. Thanks to the current climate regime, the Great Lakes have an abundance of fresh water. Climate history has shown, however, that this may not always be the case.

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III. Second Plenary Session: Modeling, Management and Design

WHAT CLIMATE MODELING MAY TELL US IN THE FUTURE

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ABSTRACT

General circulation models (GCMs) are being asked to provide increasingly more accurate assessments of changes in water resources associated with the projected climate change. To fulfill this function, some fundamental (large-scale) questions have to be answered: what will be the magnitude of climate change, what will be its latitudinal distribution, and what will be the climate's response time to greenhouse forcing (associated with ocean uptake of heat). Were these issues to be answered to our satisfaction, there would still be the questions associated with local (small-scale) response of the climate, and in particular of the land surface/ground hydrology system.

In all these areas, work has been progressing. In particular, more realistic land surface models are now being incorporated into GCMs, coupled ocean/atmosphere models are being developed and run, and there are some attempts to include cloud liquid water budgets (which could affect the magnitude of the climate change), although many uncertainties exist. The difficulties of these problems cannot be overemphasized. Nevertheless, the opinion here is that if the continuing results imply that large hydrologic changes are to be expected, the general pattern and magnitude of future water resources may be estimable, which would affect both large and small scales.

RUNOFF TO MANAGEMENT

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ABSTRACT

General circulation models (GCMs) are widely used to predict climate consequences of continuing accumulation of atmospheric CO_2 and the resulting additional greenhouse warming. GCMs represent atmospheric processes on a global spatial scale, using a grid whose cells are generally thought to be too large to capture phenomena that dictate the climate over regional or basin-sized sectors. Thus, while global energy balances are reasonably well accommodated by all the popular GCMs (i.e., all of them predict some global warming), the interpolated mesoscale implications can differ widely. This is the scale on which risk is assessed and, perhaps, also mitigated by the works of man. Water resources management decisions in a stochastic world concerned with, and threatened by, climate change are based on a combination of science, engineering, economics, regulation, tradition, and predictions derived from one or another of the GCMs. This paper addresses some of the issues that arise in making these decisions responsive to the outputs of the models of basin meteorology and hydrology. This task is made more difficult by the disproportionate importance of hydrologic extremes. These extremes often are site-specific and idiosyncratic so that the prospect of climate change cannot readily be mapped unambiguously into new values of runoff and then into optimal or near-optimal management decisions. We need an enhanced calculus of risk analysis that provides ways to ask, and to process responses to, questions about risk perception for extremes and their role in water resources management.

INTRODUCTION

We have models for almost everything in water resources planning and management. We can, on machines of varying power and with varying degrees of success, call up deterministic or stochastic models to map economic activities into estimates of CO_2 production, then convert that level of CO_2 production into an atmospheric burden of greenhouse gases, then into a prediction of incremental greenhouse warming, continuing into modified precipitation and temperature, into changes in the basin's metabolism and water budget, then into changes in soil moisture and runoff, and finally into schemes for resources management and policy. We can exert considerable control over the system at the start of this causal chain. Given the incentive and the will, we have in hand much of the technology required to alter our economic activities and, to a lesser extent, to reduce CO_2 emissions and their sequelae. Similarly, we can make choices at the end of the chain, where we introduce management and policy options. The inherent model fuzziness in the several mappings induces a discomfiting level of uncertainty into the decision-making process. This uncertainty tends to increase with the length of the causal chain. If each mapping or transition in that chain has an irreducible random component, the cascade of all such elements builds an impressive, and perhaps fatal, level of uncertainty into the policy recommendations extruded at the end of the chain. Thus it is more efficient to influence the decision at the downstream or policy end rather than at the upstream or process end of the chain because there remains less opportunity for accumulation of residual uncertainty in the process. But this might be technologically difficult to do, inviting us to note that the standard comparison between an ounce of prevention and a pound of cure is valid, if at all, only in a deterministic world.

A close reading of the literature on water resources management under real or perceived climate change reveals a commonly used approach that has not changed much in the 15 or so years since its promotion by Harry Schwarz (1977). The precipitation and temperature records are assumed to vary by a few percent in either direction and a few simulation runs are made to test the adequacy of an existing or proposed control system. In some studies, the actual hydrologic record is merely scaled up or down by a specified range of percentages while in others the means and standard deviations are perturbed by a few percent in either direction prior to generating synthetic traces of precipitation and, perhaps, of temperature. This follows from the notion, more or less confirmed by all the popular GCMs, that annual precipitation under the 2 X CO_2 scenario will be some 10 percent to 12 percent higher than that under the 1 X CO_2 scenario. A number of simulation runs are made with several combinations of potential change in the moments of precipitation or runoff and, if the simulation model is sufficiently detailed, in the moments of temperature, from which robust designs and operating policies are sought.

There remains some question as to the range of variation to consider. Note that the suggested changes in precipitation moments are based on comparisons between two sets of model-driven results, *not* between model-driven results for the 2 X CO_2 future and ground truth. This curious preference for the model output over the data might be more defensible if the model closely reproduced the observations, but this is not always the case. In one widely used set of precipitation predictions, the model's outputs differ from observations by as much as 50 percent, thereby throwing into serious question the validity of derived runoff values and management schemes.

THE ROLE OF HYDROLOGIC EXTREMES

When synthetic flows were first proposed over 30 years ago, one of the proponents harbored the hope that they would lead to obvious and major improvements in design, and that clients, government agencies, students, and deans with splendid offers would converge on Cambridge (Fiering, 1962). But only a few of these happy results ensued, and for a number of reasons. First, there was general distrust of the use of random numbers and computers in designing important things like dams. Second, there was the observation that the old designs, based on critical period analysis and firm yield as estimated by mass curves, were doing quite well. It was not until much later that we learned how forgiving a storage system can be when it is not stressed very hard, and that the average level of development in U.S. reservoirs was some very modest level of about 65 percent (Fiering, 1962; ca. Langbein, 1966), which left an enormous factor of hydrologic safety (as contrasted to structural safety, quite another issue). There appeared to be little call for these random numbers! And finally, we did not talk about risk, at least not in public. The concept of *safe yield* was firmly entrenched; we were living amid hydrologic and economic plenty.

But the rules of the game have changed dramatically. Increasing water supply demands have begun to stress the reservoir systems and have encroached upon flood storage pools with consequent increases in flood risks. New construction is unlikely, and good management cannot wring much more out of many of our systems. Thus climate change, real or anticipated or merely threatened, will require that we make disciplined inroads against our deterministic heritage; we are going to have to talk about, assess, and accept levels of risk that heretofore have been anathema. This inescapable fact demands that we consider the awkward statistical issues surrounding the analysis of extremes.

STORM FREQUENCY AND SPACING: AN EXAMPLE

Consider the several flood control reservoirs designed and built in the Northeast in response to Hurricanes Connie and Diane in August 1955. The storms struck a few days apart, with catastrophic results. Demand for municipal water supply in the region served by these reservoirs continues to grow, and construction of major new surface supply facilities is unlikely. But because the flood control reservoirs were designed to control massive amounts of runoff, they rarely are stressed by the current hydrologic regime and they stand as a reminder of an earlier set of priorities and design criteria. Efforts to manage the system by reallocating some of this generally unused flood storage in favor of municipal water supply requires assessment of the increased flood risk induced by such reallocation. Conventional analysis is of little help. The design event appears to be a true outlier, and no convenient statistical distribution can accommodate the hurricane's blip far out on the right-hand tail. To move from runoff to management we must have plausible assessments of the effects of this outlier on management and of the climate on the outlier.

First we divided the long precipitation record into hurricane and nonhurricane populations, and modified the standard synthetic hydrology algorithm to draw an additional random number on the basis of which the year was classified as a hurricane or nonhurricane year. (It no longer is necessary to recite the litany of models and modelers adumbrated by this strategy.) This gave two groups of synthetic events using moments estimated from the two sets of observations. But even these modified traces did not produce synthetic hurricanes as severe as the 1955 event, whereupon it was impossible to assess reliably the increased flood risk due to storage reallocation, and to determine how this risk would change with climate. We had the wrong model.

The next modification explicitly recognized the profound effect of the near simultaneity of the two hurricanes. While both were major events, neither taken alone was an outlier among the population of hurricanes; only their combination was. Therefore we abandoned the notion of finding a statistical fit that would tolerate the massive combined runoff, and we modified the synthetic hydrology generator to accommodate the possibility of two hurricane floods during the same period of the reservoir simulation. This modification forced consideration of the interval between hurricanes and the amount of warning time available prior to each. Clearly the reservoir could be drawn down, if not evacuated, whenever early tracking information suggested a high probability that a hurricane would make a nearby landfall and produce hurricane runoff impacting the system. There is little chance that a major storm would escape early detection. However, there remains a significant risk that a false positive alarm might be sounded, with all of its attendant inconvenience, political cost, and real economic burden. We assumed that the reservoir was always drawn down when the first hurricane arrives, and we did not study the likelihood and effect of false alarms; this is a subject for future work.

Let us assume that we are in a hurricane month. We then sampled a random number to determine if another hurricane would arrive within the same month of the simulation. If *not*, the program simply superimposed the single hurricane over the basin, calculated the associated runoff using a basin model with an appropriate random component, and routed the resulting runoff through the reservoir system in the usual fashion. If *so*, another hurricane storm was generated and its separation (in days) from the first was drawn at random from an empirical distribution based on records of hurricane tracks and landfalls in the North Atlantic. Between storms, the reservoir was lowered as rapidly as possible to accommodate the second event, whose runoff was similarly estimated so that the combined hydrograph could drive the reservoir system. While these derived hydrograph results were more nearly in conformance with observed extrema, we still were unable to reproduce the maximal historical runoff despite a very long synthetic record. Thus we knew that system management schemes suggested by the model might be compromised, inadequate, or totally incorrect. We did not proceed with the results at hand; ground truth was not reproduced closely enough, and we had to improve the model.

A more conclusive modification was suggested by the realization that the basin will change after the first hurricane. The parameters of the basin model include infiltration and evaporation coefficients and a groundwater coefficient that governs the rate of return flow to basin output. Since hurricanes occur during the summer, snowpack accumulation and degradation are irrelevant. Immediately after the first hurricane passes, these basin model parameters change dramatically. The infiltration is basically shut down, the evapotranspiration is sharply reduced, and the groundwater storage increases enough to warrant concern that the model's simple linear representation for return flow is inadequate. The scour, erosion, and reduction in channel capacity caused by the first storm prompt the effects of the second to be exacerbated. This exaggerated outcome wanes as the basin returns to its normal condition in the interval between floods and as the parameters of its model approach their standard values.

There is, however, a paucity of data on which to base a rational scheme for adjusting the parameters, so we made plausible adjustments and then sweetened these using agreement with the single observation (1955 flood) as the criterion of fit. The resulting parameter assignments are not unique, and we have no way of knowing how rapidly the basin parameters revert to their nominal values.

Despite these difficulties, by juxtaposing the two storms and perturbing the parameters of the model for the second one, we reproduced within a few percent the peak runoff recorded in August, 1955. This leaves the following questions: Under climate change, will there be significant changes in the following:

- The proportion of hurricane (or more generally, of extreme) years
- The moments of the nonhurricane events
- The moments of the hurricane events
- The clustering and temporal separation between successive hurricanes
- The parameterization of the basin model(s)
- The demands for the resource, in terms of quality, quantity, and patterns of availability
- The regrets associated with not meeting these demands
- The criterion or criteria used to make design choices

Some of these items fall into the natural sciences and some into the social sciences. In our work in the Northeast, system designs reflected one dominant hydrologic outlier. It is at least difficult and perhaps impossible to obtain reliable statistics that describe the relative importance in any project of extrema versus that of ordinary events. Note this is distinct from tabulating the fraction of total reservoir storage space or cost (or benefit) reserved for flood control versus that for water supply, industrial use, or irrigation. Many systems can be designed to control less extreme floods, for which "a calculated risk" can in fact be calculated and either accepted or rejected. In the Connie/Diane problem described here, there was no pre-1955 experience with such clustered storms, and hence until that time there was no plausible reason to have expected them. There is a difference between being merely overwhelmed by a large flood event and being truly surprised by an outlier (Fiering and Kindler, 1987; Villamarin, 1988). The storm of August 1955 was surprising and, had it not occurred, it could be argued that we should not be held accountable for not anticipating it even under climate change. However, the unthinkable *did* occur and, even without climate change, we are forever alerted to the prospect that it will occur again. It is not likely that we can defensibly calculate the probability that it will recur within the next 50 or 100 years except to state that the probability is small. But will it be larger than it was in 1955? Has the mere occurrence of the event changed our perception? Has the world actually changed due to warming? Will it change? If so, will these changes affect the inputs (e.g., runoff) to our engineered water resources systems? And if so, how do we account for all of this in our designs when we cannot rely on the comfortable notions of expected losses?

REGRET, MANAGEMENT, AND THE DECISION PROCESS

The problem of very rare, very large losses is an old one in statistics. Many recognize it as Bernoulli's Paradox, and in recent years it appeared in the guise of consideration of nuclear plant safety, an issue characterized by very small probabilities of very large losses and by the realization that the product of these alone; i.e., the expected loss, was inadequate to characterize society's perception of the risk. If there were a number of historical closely spaced hurricanes (or less severe tropical storms) from which the distribution of storm intervals could be deduced empirically, and if there were an adequate theory for calculating the modified distribution of such intervals on the basis of thermodynamic considerations, we would in principle be able to predict the impact of climate change on storm runoff and then, following standard practice, the impact on (reservoir) system operation and ultimately on system response. The various sensitivities and elasticities could be estimated. But there appears to be no such theory readily available. In a recent (1990) study relating the 1981-1986 rise of the level of the Great Salt Lake to anomalous mid-tropospheric wind patterns, Namias (1990) noted that precipitation over the Great Salt Lake is a reasonably good index surrogate for mean national precipitation and that "...spells of excess or deficient precipitation over the United States for seasons and years are closely associated with [mean] abnormalities in the general circulation. The complete understanding of these interactions leading to their prediction remains one of the principal problems facing meteorology and climatology, and comprises a central problem...." Thus our science and our data base appear inadequate to the task of explaining or correlating the clustering of periods of excess precipitation, and by extension, to the further task of predicting changes in the distribution of the interval between events. Perhaps such power will soon become available, and we might better be able to predict inter-arrival times. This is the subject of continuing research.

But a few approximations can be attempted. Suppose the hurricane "season" in the region of interest is set at 90 days (any other value would do). Suppose further that on average 10 Atlantic hurricanes occur each year, and that half of these pose potential threats to the region in question. These values are plausible for order-of-magnitude calculations. Thus 90/5 or 18 days is a lower limit to the mean interval between hurricane arrivals. Because all storms do not affect the same area (say the Northeast), the actual mean inter-arrival time is somewhat longer. However, it is important to include less intense tropical and extra-tropical storms. Let us note simply that some reasonable estimate of the mean inter-arrival time can be obtained, and that it might be of the order of 20 days.

We assume that the inter-arrival times between all intense storms are derived from a Poisson density. If the mean is taken, say, as $\lambda = 20$ days, we can calculate the probability that the interval will lie in the ranges 1-5, 6-10, 11-15, 16-20, and >20. These interval widths are chosen to bracket a reasonable range of times associated with recovery of basin model parameters. The first hurricane perturbs the basin parameters, whereupon these new values govern the system for 5 days during which there is a specified probability that another storm will arrive. If not, the parameters recover a bit and the calculation is repeated for the next 5 days, and so on until the basin is fully recovered and the simulation marches into the next month. In this way we attach probabilities to the various intervals and hence to their combined (but diluted) effects. Different responses, attained for varying values of λ, show wide ranges of similar response within which robust decisions might be made.

A formal statement of the planning objective immediately encounters inconsistencies. Suppose the reliability (against flood damage) of a given system is 0.99 so that it is expected to fail every 100 years, taken to be a tolerable level of risk. If the reliability under presumed climate change is estimated to fall to 0.98, a reduction of about 1 percent, the return interval drops to 50 years, a reduction of 50 percent. This is a very sensitive measure of performance. Given the uncertainties and assumptions explicit in the suggested characterization of the problem as a Poisson model, and given the subjective estimates of changes in basin parameters, it is clear that the precision of results cannot be expressed in single percentage units and that formal scalar optimization has little justification. Hence, some other form of decision analysis is indicated.

Matalas and Fiering (1977) promoted the concept of regret in water resources planning, building on some earlier work by Rogers (1969). The goal was to use operational mathematics in negotiations over water resources. Whatever optimization scheme is imposed is unimportant for the moment; the point is that the political process, imputed levels of risk aversion, societal preference structure, and the whole gamut of planning techniques and methodologies are to be brought to bear. Some years ago the Harvard Water Program made a strong case for Paretian Environmental Analysis (Dorfman, 1972), emphasizing tradeoffs along the stochastic negotiating frontier. Fiering and Rogers (1989) demonstrated the use of regret in a water resources context involving climate change, and are extending their approach to the effect of climate change on the Great Lakes.

CONCLUSIONS

The selection of an unambiguously superior option does not appear to be a suitable objective of the resource planning process under conditions of potential climate change. Rather, as has been suggested by a number of studies but most notably that by the National Academy of Sciences (Committee on Science, Engineering, and Public Policy, 1991), a sensible plan would be to undertake those activities, and make those resource-based decisions, which can be supported even without climate change, and await further study. The science community is traditionally conservative when it comes to asserting and defending policy based on tenuous conclusions. The integrity of the investigator, and his or her institution, is held to be on the line. But in matters of choice based on selecting one model over its competitors, we are forced to be Bayesians whether we like the idea or not, and we must weigh the prior expert judgments with empirical evidence while accounting for the sensitivity of the solution to these priors. This sensitivity, after all, is the standard basis for attacking Bayesian analysis. But it is precisely here, in assessing and communicating the role of prior assessments, that people of good will must become engaged so that the public can learn how much of the risk they are being asked to bear can be attributed to differences in subjective estimates and how much to objective evidence. We in the science community cannot simply surround our best judgments with estimated error bars or standard errors and walk away.

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DESIGN IMPLICATIONS OF CLIMATE CHANGE

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ABSTRACT

In the context of water resources development (as well as in most other contexts), the possibility of a climate change occurring within a few decades translates into an increase of uncertainty to be considered. In general, any increase of uncertainty should lead to a higher degree of hedging and hence to a greater robustness and operation flexibility of projects.

It is argued that, vis-à-vis the common degree of uncertainty that a prudent design of water resources projects should now routinely accommodate at any rate, its addition corresponding to the current estimates of the extent and rate of immediate ($\approx$ 50year) climate changes is not too dramatic and in most cases can be accommodated by periodic revisions of the "soft component" of the projects; i.e., by changing their operation in concert with new water management realities.

This argument is developed on the background of historical experience in water resources design and operation, analyses of hydrologic uncertainties, and observations over several decades of changes on the demand side of water resources systems, including changes in public attitudes toward water projects.

The author's conclusion is that the issue of climate change has been blown out of all proportion, both as to the actual degree of its current understanding and as to its potential impacts on the planning and design of water resources projects. Its alleged importance seems to be a convenient excuse for the current runaway expansion of consulting business in simplistic mathematical modeling and, on the political scene, a convenient smoke screen behind which more important and urgent issues can be hidden and attempts at their solutions avoided.

INTRODUCTION

In his inspiring book, Bohm (1957) observed that there is a common pattern in all sciences: They start with description of phenomena and, "only after (they have) reached a fairly advanced stage of development," they progress to their mature stage, which is concerned with causal explanations. In this sense, climatology has just about entered its "stage of maturity," having, so to speak, graduated from the framework of descriptive geography to that of geophysical dynamics. However, in spite of many important discoveries and developments made in the past few decades, climate research is only now starting to implement a comprehensive global research program and build up an adequate global data base necessary for a systematic testing of current theories and models. In the many years before such data sets become available from projects like EOS, GEWEX, etc., new discoveries are likely to be made, theories modified, and predictions revised.

The present climate models still capture only the rudiments of the physical system they aspire to portray, are based on as many (or more) assumptions and extrapolations as they are on real data and known facts, and necessarily miss many crucial aspects, either because they are not yet known or are beyond the current modeling capabilities. The margin of error of their predictions of the possible climate changes caused by anthropogenically induced changes in the chemical composition of the atmosphere may well be of the same order of magnitude as are the predicted changes themselves. However, what in my opinion is more important is their demonstration in principle that, based on the current level of scientific understanding of the causal chains linking the various elements of the climate, the by-products of what is euphemistically called "development" may become a significant element of the climate system. One distinct possibility of its manifestation is a global warming within an historically short period of time, with potentially large adverse effects on society.

This is enough to make the human race pause and reexamine its modus operandi. A prudent response seems to call for the following:

1. Containing the primary sources of danger that are already in operation

2. Neutralizing the causes that have led to the present situation

3. Learning more about the functioning of the global system so as to see its weak and fragile elements more clearly

Task number 1 requires action by the big players, namely governments and large corporations; task number 2 translates into changing the attitudes of the population at large; and task number 3 calls for research by which I mean an activity leading to an enlargement of the body of knowledge relevant to the object under study.

The problem with task number 1 is that, to be effective, the required action would often have to be so drastic that there is not enough political will to undertake it. The reluctance to admit this leads to various evasive maneuvers, one of which is to call for gathering "more information" first.

The problem with task number 2 is that the essential prerequisite for its success is a substantial strengthening of the role of ethics at all levels of human endeavor (personal, public, corporate, scientific, political, environmental, etc.). The chances of this happening can be judged from the results of similar efforts of countless religious movements over the millennia of recorded history.

The problem with task number 3 is twofold. First, the acquired knowledge is not necessarily applied. Second, its acquisition is expensive, takes a long time, and the research often does not seem directly relevant. This gives it a rather low priority in most organizations. Typically, only the immediately desirable end products have a high priority but the means needed to get them have a low priority. For example, in the 1980-1981 action plan of the research institute where I used to work, "determination of runoff characteristics in ungauged areas" and "impact of man's activities on drainage and flooding" had "high priority"; "development of transposable and verifiable watershed models" had "medium priority"; and research on "effect of soil moisture on the relationship between precipitation and runoff" had "low priority"(Klemeš, 1980). This ties neatly in with the problem mentioned in connection with task number 1 above and is one of the reasons for the proliferation of climate-change-impact studies despite a conspicuous absence of an adequate scientific basis for them.

All these problems are relevant to the theme of this conference and to the topic of this paper. Some of them will be elaborated on in the following sections.

Climate Research and Modeling of Climate-Change Impacts

I want to make a very clear distinction between these two activities. *Climate research* is a serious business. Its results gradually may give us a better picture of the climate system, its predictability, sources of vulnerability, etc. It is important, however, to realize that while on the one hand it may provide us with more specifics, thus reducing the current level of the related uncertainties, on the other hand it may reveal a greater amount of uncertainty in the system than is the current consensus, thus lowering its predictability far below the present expectations. Such, for example, has been the result of research on the fluctuation of streamflow. Its justification has always come from the hope that more knowledge will reduce the uncertainty associated with its future behavior, thus reducing the cost of water resources projects, in particular reservoirs for streamflow regulation. What happened was just the opposite. At an early Canadian precursor of the present conference, I gave the following example of this development (Klemeš, 1980).

In 1915, in a report on the design of hydropower developments for the Winnipeg River, its author (by all accounts a very competent engineer), basing his statement on the then-available 7-year-long streamflow record, felt confident to conclude: "To sum up, it may be said that the general runoff conditions in the power reach of the river would warrant the assumption that a fairly complete regulation of the river can be obtained." Sixty years later, two distinguished hydrologists cautioned that even 100 years of flow records may not be enough to "attach reliability to any results" as far as storage for complete regulation of flow over a given period is concerned. This, of course is even more true now, after almost two additional decades of research have revealed the additional uncertainty due to a possibility of climate changes occurring within the useful life of storage reservoirs presently on the drawing board.

In contrast to climate research, the *modeling of impact of climate changes* on water resources in any particular geographical location cannot, in my opinion, be regarded as a serious business. The "scenarios" that such modeling produces are exercises at the level of undergraduate projects or, at most, master-degree theses level where the purpose is to demonstrate an individual's ability to use some standard procedure, sort out obtained results, and report on them in an intelligible manner--in other words, to simulate an approach to a real-life problem. The only difference is that these exercises have been officially sanctioned as serious business. In my view they are not, for many reasons.

First, they use a (1) modeling technology (GCMs or conceptual hydrologic models) that has been developed for different purposes (research tools or transfer functions from climate to runoff under known stationary conditions), (2) a technology that itself is still only in an experimental stage and subject to changes), and (3) a technology that, at this stage, purposely leaves out crucial elements that may prove decisive in many specific cases.

Second, in the impact studies, these models are invariably used by analysts who have not developed them, and may be only vaguely familiar with their structure, assumptions, limitations, etc. As a result, the generated scenarios may often be intrinsically wrong because of possible physical inconsistencies due to arbitrary combinations of changes imposed on model inputs and parameters.

Three, the impacts are, as a rule, generated in isolation from impacts of other processes, both physical and sociopolitical, most of which are largely unforeseeable for a 50-year-or-so time horizon commonly assumed in the scenario-generating computer games.

Four, the overkill of scenarios that now are routinely generated for a given case have no information content for a specific decision such as a design, since, as a rule, there is no clue as to their relative merits. Coming up with, say, 150 different scenarios (the only tangible difference from 10 years ago is that then 15 scenarios were closer to the norm) is just a convoluted and pretentious way of saying "I don't know." This is not information, it is information pollution.

Five, scenarios invariably portray some stationary situation "after the change," which may be very far removed from the desired "discrete snapshot" of a gradually evolving scene.

I could go on with these caveats but other more qualified authors have written about them in some detail and with impressive eloquence (Reifsnyder, 1989; Philip, 1991). Should there be any doubt as to the conservative nature of my above comments, I may be permitted to quote a few key pronouncements from these references: "... quantification as camouflage ... craving without content...ultimate vacuity that can follow when man abandons using his mind in favor of the computer...."

Climate-Change Impact on Water Resources and Project Design

The general message from the current climate-change research is that the climate can get "worse" (if it should get "better," we need not worry, I suppose). This can be translated readily into impacts on water resources, with no need for models, computers, scenarios, sensitivity analyses, algorithms and esoteric jargon. It boils down to the possibility of the following:

- Less water available
- Greater extremes
- Less advantageous seasonal distribution of precipitation and/or runoff

And everybody seems to agree that, at present, it is not possible to quantify the possible changes for any specific geographical location, either in extent or in time of occurrence, or even in their direction (Gleick, 1989). To quote from a recent USGS report (Moss and Lins, 1988, p.10), "Although these new hydrologic uncertainties certainly exist, the current level of scientific understanding does not permit their quantification."

Indeed, the only relevant message recited over and over again in the conclusions of the untold tons of climate-change-impact-on-water studies is this: "Be prepared for adverse changes, don't waste water." What a big discovery, what a mouse born out of the mountains of computer printout! A message repeated in every introductory course on water resources given during the past 50 years; a message true regardless of any climate change; an established fact of life already causing hardship in many parts of the world. A message so basic and well publicized (and pertaining to all natural resources) that every water resources engineer worth his salt, if not every only moderately literate layman, should by now have it encoded in his genes, so to speak.

This is why I propose that water resources planners and designers have nothing new to learn from the present climate-change-impact-on-water studies and can safely ignore them. Not to waste and pollute water--to hedge against the possibilities of droughts and floods more severe than the historical ones--has long been a part of professional ethics in the water resources trade. This time-honored practice has, in general, led to robust and resilient designs characterized by multiple-purpose projects, adaptable operating policies, wide safety margins, contingency plans for extreme conditions, etc. It should not be overlooked that because of these features, a vast majority of old water resources projects continue serving the community well, even long after the original design parameters and assumptions have changed.

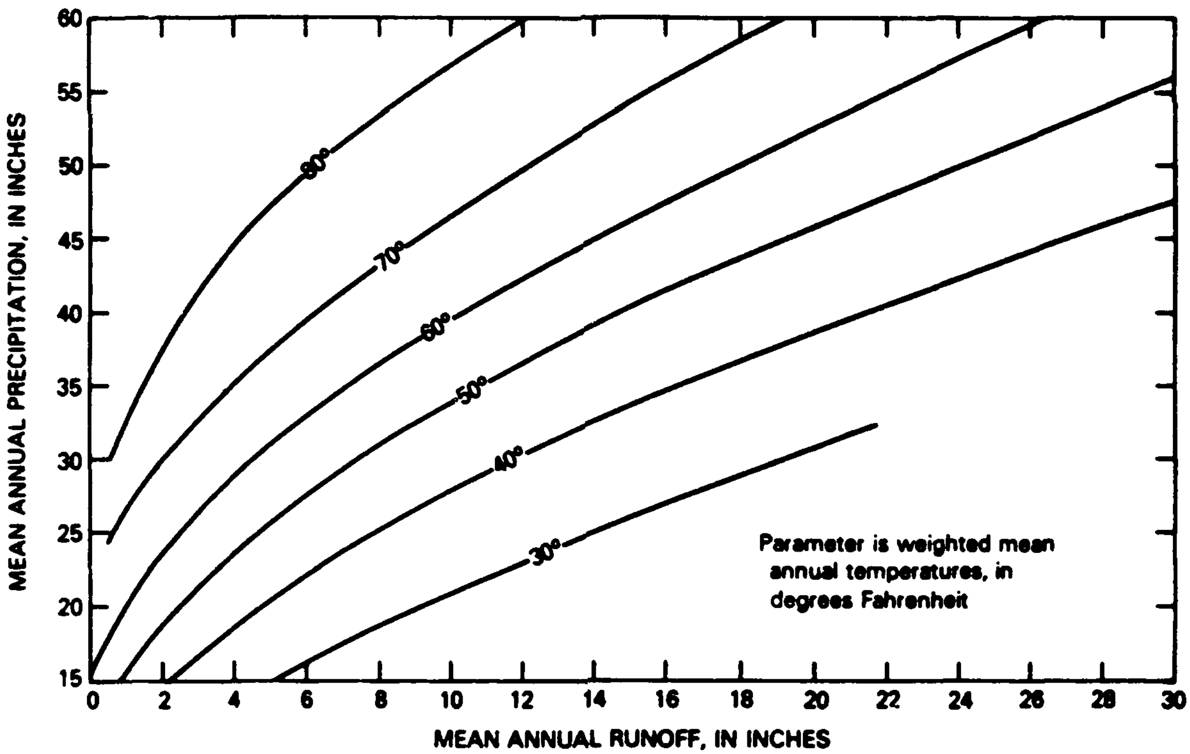
This, by the way, is not a new discovery of mine and I am repeating it merely for the benefit of those who may have missed this well-known fact in everyday life and in the literature where it has been noted and analyzed quite some time ago. For example, Matalas and Fiering (1977) concluded that "...it is comforting to recognize that most large (water resources) systems contain so much buffering that resilient design can be achieved operationally without recourse to sophisticated or elaborate projections about the climate."

Another reason for my opinion expressed above is this: Even if some of the worst current scenarios should materialize, the overall character of the changes envisioned is rather benign compared with many other possible changes. They are gradual and spread over decades (Reifsnyder, 1989), thus offering an opportunity to accommodate them by phasing in the appropriate measures as they become necessary, basically in the same way as is routinely done to accommodate (and/or control) growth of water demand due to other causes.

As a consequence, I consider it irresponsible, when, say, the federal Canadian Climate Centre commissions (and publicizes in its *Climate Change Digest*) studies whose only conclusions are, for example, that some 30 to 50 years from now "ski-resorts in Eastern Townships and the Laurentians would be unlikely to operate during the Christmas holidays without significant snow-making facilities," that water demand for lawn watering may increase and a new and costly infrastructure would be required to meet it, that intensification of publicity campaigns to preserve drinking water is recommended, or that the golfing season in Montreal may extend "mainly during spring and autumn" and the "opening of new golf courses would then be likely" (Environment Canada, 1988, 1989). Speculation at the scientific level of these pronouncements leads me to propose the following climate-change-impact-scenario impact: Inspired by the latter warning of Environment Canada and eager to seize an opportunity to provide national leadership in the prevention of climate-change impacts, the municipality of the village of Oka near Montreal opened a new golf course, the impact being a national crisis and a military confrontation between Canada and Mohawk Indians.

Unfortunately, the Canadian Climate Centre cannot be held legally responsible since its *Climate Change Digest* prominently displays, in both official languages, a disclaimer that "... the opinions expressed herein ... do not necessarily state or reflect those of the Government of Canada or any agency thereof." What a farce, what a masquerade of disinformation at public expense!

I suggest that for the speculations (and we can do no more than that) about possible impacts of possible climate change on the hydrologic regime in specific locations across North America, that the 40-plus-years-old chart (Figure 1) of the distinguished late American engineer and hydrologist Walter Langbein, which gives an empirical relationship between annual runoff, precipitation, and temperature (Moss and Lins, 1988), is still much more valuable than all the hundreds of computer scenarios put together.



Source: Langbein et al., 1949; reproduced from Moss and Lins (1988).

Figure 1. **Relationship of annual runoff to precipitation and temperature.**

Uncertainty in Water Resources Projects: Some General, Hydrologic, and Water-Demand Contexts

There is no need to dramatize the uncertainties inherent in the possible climate-change effects on water resources projects. There is no tragedy in the fact that decisions (e.g., designs) must be made based on incomplete information. This has always been the rule rather than the exception in real life, although it may be a revelation to somebody brought up in the age of "information explosion" and the self-serving multi-billion-dollar propaganda of the information-related industry (media, computers, communications, etc.) for which creating an illusion of indispensability of all sorts of "information" simply means good business.

As Ortega y Gasset said some 50 years ago, "Life cannot wait until the sciences have explained the universe scientifically. We cannot put off living until we are ready" (Philip, 1991). In fact, the very concept of "decision" implies the existence of uncertainty since in a deterministic Laplacian world there would be nothing left to be decided. Only in the face of uncertainty are decisions relevant. A patient hardly needs a diagnosis based on complete information obtained from his autopsy! In the same vein, a perfect design could only be made at the end of the useful life of a project.

To put the uncertainty due to a possible climate change in perspective, I will give a few examples of changes that some water resources projects did encounter during historically short time periods.

Water Availability

For the Colorado River, the apportionment of its water and the design of the Hoover Dam were based on a long-term average flow the estimate of which now appears to be at least 20 percent too high (Dracup, 1977). This corresponds to the situation that a project designed now on the basis of some present runoff parameters might face in the middle of the next century, given a typical climate change presently envisaged. Taking the present situation in the Colorado River basin and in the areas dependent on its water as a prototype of a "post-climate-change" situation elsewhere, we see that the problems to be addressed are basically of two kinds: (1) renegotiation of the apportionment so as to make it better correspond to the actual water availability and existing demands and (2) increase of water use efficiency. Of course, if a convenient additional water source were available, its development might be a welcome alternative; if not, a modification of the "soft component" of the "pre-climate-change" design will have to do. However, this is exactly the common practice of water resources management since, regardless of any climate change, water demands and the socioeconomic climate do always change during a half century.

One also has to see the changes in long-term hydrologic averages (this is the "reality" of the "climate-change world") in the context of the short-term fluctuations that constitute the basis of the actual water management of any project. For illustration, the 10-year flow averages in the Colorado River (at Lee Ferry, Colorado) fluctuated in the past within about +/- 30 percent of the long-term average, so that even such a large climate-change impact as, say, 20 percent can be more or less conclusively detected only several decades after the fact. During all that time, life would go on--as it did in the Colorado River basin during the past half century--forcing gradual solutions to the gradually more severe and frequent stresses on the existing water resources and facilities.

The masking effect of short-term fluctuations (called anomalies by climatologists) of precipitation, streamflow, etc., can hardly be overemphasized in the context of climate change and its impacts. They are the stuff of real life, they are the *normals*, while the "climate normals" are the *anomalies*--artifacts of ex-post-processing of past observations--a post-mortem diagnosis of the climate, if you wish.

Design, of course, is concerned with longer periods than day-to-day water resources management, both in regard to hydrologic and climate data it uses and to the water demands it anticipates. Nevertheless, even design is greatly affected by natural fluctuations that are considerable over relatively long periods even under supposedly stable climate. For example, consecutive 18-year averages of streamflow in a 100-year record of the Elbe River (at Děčín, Czechoslovakia) fluctuated within +/- 25 percent of the long-term mean and the standard deviations of annual flow totals for the same periods from -50 percent to +100 percent (Klemeš and Němec, 1983). It has been demonstrated (Klemeš, 1979) that if a storage reservoir for a given level of flow regulation were designed independently on the basis of each of the four consecutive 25-year periods of this record, the resulting reservoir capacity would vary from zero to 3×10^9 m^3, with the 95 percent confidence ranges themselves varying from about 10^9 to 3×10^9 m^3!

Such are the typical uncertainties in hydrologic data that the designer of water resources projects is used to dealing with--and his record of success has been remarkably good. For this he owes much gratitude to people like Hazen, Foster, Hurst, Kritskiy, Menkel, Langbein, and others (Klemeš, 1981) whose names most likely are unknown to most contemporary scenario generators but who, without the "benefit" of easy computing, laid the foundation for risk analysis and quantification in water resources design during a 50-year period starting in the second decade of this century.

Water Demands

Large as they may be, the water supply (hydrologic) uncertainties are benign compared with those related to water demands that in the stage of planning and design are unknown and hence unquantifiable--the true "unkunks" (unknown unknowns), as the "unknowns that cannot be deduced from what is already known" were labeled by the U.S. Air Force (Linstone, 1977). Here I will limit myself to only one example from my personal experience (more can be found in Klemeš, 1990).

In the early 1960s, I was charged with the elaboration of a new operating policy for the Brno Dam (Czechoslovakia), intended to accommodate a new priority--*recreation*. The dam had been designed about 30 years earlier for *irrigation*. About the time its construction was finished, the "unkunk" of World War II occurred. The irrigation facilities were not built but, instead, war industries were forced into high gear by the German occupation forces and the dam (which happened to have a hydropower plant attached, only in order "not to let the water flow out just like that" as its designer told us, snapping his fingers, when he was our professor in dam construction in the 1950s) was operated to maximize *power generation* for the energy-starved city of Brno. Immediately after the war, its operation was changed to maximize *flood protection*, in the wake of the fresh memories of heavy flood losses in the wet early 1940s. However, as the Brno population grew rapidly after the war, and the new Communist regime threw all resources into the construction of facilities for heavy industry, there was no money for building a badly needed water supply system for the city and the use of the dam was changed to *water supply*. Thus, within less than 30 years, the main water demand for the dam had five different foci; it served all of them well (ironically, its designer, a kind man and later a wise professor, was dismissed from the Technical University of Brno by the Communist regime as unfit to instill desirable "socialist qualities" into students).

This may seem an extreme case but it is so only because it pertains to a situation where a water resources project had to respond to gigantic political and socioeconomic changes telescoped into a period spanning only one generation. However, even on this continent, without comparable extreme changes in the political climate, the changes in water demand have been considerable. Thus the chairman of the Subcommittee on Water and Power and co-sponsor of the Western Water Policy Review Act now before Congress is quoted as saying that "With a demographic shift in the West from agricultural to urban areas over the past 30 years, water is needed in cities in the West, not rural areas" (Bush, 1991).

Some Issues of Ethics

At first sight, the difference between the ethical and the unethical seems clear and simple. One has a very definite "gut feeling" about it and, should there be any doubt, ample guidance is available--from Codes of Ethics of the various professions to commandments of various religions, admonitions of ancient philosophers as well as contemporary public figures, and graphic historical examples of ethical and unethical conduct. Yet, things tend to get complicated and the complications tend to increase with the exertion of the intellectual effort to grasp the problem and with the increasing complexity and sophistication of life.

For example, my ideal as a professional and a scientist has always been to live up to the standard set by Confucius: "When you know a thing, hold that you know it, and when you do not, admit the fact--this is knowledge." It pleases me to see it advocated and applied in practice. I greatly appreciate, for instance, the fact that "...in the early days [of the BBC]...when nothing newsworthy was deemed to have occurred, [the newsreaders] said so and played classical music instead" (McCrum et al., 1987). For the same reason, I have often quoted M. Fiering's (1976) statement: "Fascination with automatic computation has encouraged a new set of mathematical formalisms simply because they now can be computed; we have not often enough asked ourselves whether they ought to be computed or whether they make any difference." I have often reread and recommended to others P. Rogers' (1983) review of a book on environmental quality management where he says, inter alia, "The engineering and the scientific community are expected to perform analyses and prediction without a proper scientific base ... (they) sorely need to be told the truth about models and the current lack of scientific certainly ... it is hazardous to use them directly for practical applications or policy decisions...." He asks the crucial question, "Why did the scientific community not refuse to collaborate with requests that are patently impossible?"

Why indeed? Rogers' answer that, under legal and administrative pressures, the scientists and engineers tried "to do the best they could under the situation" represents only a part of the picture--the second one. The first and more important one lies at a deeper ethical level and is contained in the answer to the following question: How much personal sacrifice is reasonable to expect in upholding an ethical standard such as that enunciated by Confucius? Would it be reasonable to expect, Dan Rather not to produce some "news" for his CBS News if nothing newsworthy happened? Is it reasonable to expect a young engineer with a dependent family to decline an assignment to model one stupid thing or another, given the prospect of losing employment and considering the fact that, useless as the assignment may be, some aspects of the work itself may be quite interesting? I can testify about the difficulty of such choices from my own experience, as a designer of water resources projects as well as a prospective climate-change-impact-on-water resources modeler.

The first time I failed rather miserably in such a practical test in professional ethics. Despite protesting the impossibility of my boss's request, I provided him within a couple of hours with a requested breakdown of costs and materials for a dam under consideration for which at the time there was neither a fixed site nor design parameters. He of course knew the utter unreasonableness of his request but the point was that the breakdown was requested by the Central Committee of the Communist Party. The space-time coordinates of the test: Czechoslovakia in the 1950s; the price tag for upholding our professional integrity: at worst, being sent into coal mines to "learn a proper respect for the proletariat."

The second time I avoided the test by a conspiracy, so to speak. Being in charge of the planning of one fairly large dam, I was deeply convinced that it was not worth the intangible losses its construction would cause, namely the flooding of a popular spa with hot mineral springs, as well as some rather unique arragonite caves (reportedly, one of only two such occurrences in Europe), resettlement of several hundred rural inhabitants into communal housing in nearby industrial towns, and more. The problem was that a brute benefit-cost analysis was unambiguously in favor of the project and there was no hope that a government adhering to the sacrosanct Marxist dogma about an absolute priority of the "economic base" over the "superstructure of intangibles" would fail to approve the project given the figures. Rather than bravely fighting for a due consideration of the intangibles, I induced a like-minded official of the Health Ministry to concoct a "cost" figure I needed to sway the benefit-cost ratio against the dam, by capitalizing the coal and steel production lost during the lengthened reconvalescence period of sick workers due to the unavailability of the sanatoriums in the spa. This was long before I came across the following advice that Machiavelli gave to Raffaelo Girolami: "...occasionally, words must veil the facts. But this must happen in such a way that no one becomes aware of it...."

It was much easier to pass the test in the 1980s in Canada and decline the formation of a group for the modeling of climate-change impact on hydrology and water resources and do other similarly "useful" things. However, by that time I was no longer a young engineer with a dependent family and an early retirement was an affordable alternative.

The moral of all this is self-evident:

- Adherence to high standards of professional ethics for a senior scientist nearing retirement or for a tenured Harvard professor is one thing; it is quite another matter for a run-of-the-mill young engineer or scientist.

- If high ethical standards are not upheld at the centers of power it may be increasingly difficult to uphold them in subordinate positions.

This section would have not been included had it not had a direct relevance to the modeling of climate-change impact on water resources as currently practiced in the United States and Canada.

CONCLUSIONS

While it is recognized that the possibility of climate change increases the uncertainty inherent in the planning and design of water resources projects, it so far does not appear that this increase is significant in the context of other uncertainties commonly present and of the common planning horizons of 20 to 30 years. Both the past experience and the present standards of practice indicate that the potential impacts can be coped with if and when changes become manifest.

The following general guidelines for the planning and design practice are considered sufficient for the foreseeable future:

- Adherence to high professional standards in proposing solutions to existing water resource problems.

- Commitment to measures limiting water waste and pollution.

- Striving for robust and resilient designs and operational flexibility of projects.

- Documenting and taking into account known uncertainties in water supply and demand.

- Documenting the ranges of feasible operation of projects, rather than providing only nominal design parameters.

- Providing a general outline of feasible contingency measures for extreme conditions not accommodated by the project under normal operation.

- Not wasting effort and resources on deep analyses of shallow facts and conjectures and remembering that, in the absence of solid scientific evidence, an educated professional's judgment is by far the best guide for action.

- Not being intimidated by obscurantist quasi-scientific jargon and computer-generated results and insisting on a clear disclosure of factual information, assumptions, and conjectures behind modeling results to be considered.

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IV. Adaptive Responses to Climate Change

ADAPTIVE RESPONSES TO CLIMATE CHANGE: LONG-RANGE PLANNING

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Adaptive responses to climate change within the long-range planning perspective are affected by a framework of considerations that include large uncertainties associated with climate-change forecasts; the economic efficiency constraints in designing infrastructure; planning that focuses on localized problems; regional differences in physical conditions and population needs; and the variety of models available to interpret the physical systems and predict long-term changes. Some in the workshop maintain that these planning and managerial constraints or considerations dictate minimal consideration of long-term climate change by water resources planners and managers. Further, some participants believe that managers have the tools, experience, and infrastructure to respond incrementally to changing conditions that climate change may bring. Others, especially climate-change modelers, argue that climate change will present a new experience outside our historical experiences. They argue that some studies indicate that extreme values of climate-related phenomena would be well outside present variation.

The above dialogue reveals a dichotomy between the purposes of atmospheric modelers and water resources managers, planners, and decision-makers. Atmospheric modelers recognize the need to improve forecasts of climate change, but believe that the climate-change forecasts yielded by the GCMs to date clearly indicate that water resources managers should begin to take climate change into account. However, improved climate forecasting is not the immediate charge for water managers and other decision-makers. They want to make better decisions and want better information on which to base decisions. The question is what is needed most in terms of data and information? Future climate variables are just one of an array of inputs needed by managers in order to understand how their systems (e.g., river basins) work--whether today or in the future. Given the uncertainties of GCM outputs, the water planners and managers may see the need to start their modeling process a lot closer to the decision-making end of the spectrum than the GCM-input end of the spectrum.

Planning horizons affect water resources project outputs. One planning horizon pointed out by Eugene Stakhiv in his paper "Considerations for Long-Range Water Resources Planning and Management Under Climate Uncertainty" deals with project outputs that are dictated by economic efficiency and in turn affected by time and the discount rate. With the relatively high discount rates currently used, short-term outputs usually dominate the range of choice. Another planning horizon is concerned with the physical reliability of structures. In cases where there is significant hydrologic uncertainty, conservative design criteria are appropriate--frequently leading to larger, more robust water systems. Given these two opposing philosophies of "optimal" water development, most water resources managers, planners, and decision-makers are ultimately influenced by financial considerations (the budget realities) and move toward a sequential process of response to changes or new demands--through tactical and contingency planning for potential emergency situations. In this environment there is little room for long-term climate-change considerations.

Water managers have long been exposed to changes, and have a wealth of experience to use. For example, federal water managers have used *Principles and Standards* and most recently *Principles and Guidelines* (P&G), which represent the cumulative wisdom gained from much experience. Even given these frameworks, systematic evaluation and decisions are political; that is, public-oriented. Other things drive decision-making--budgets, floods, and droughts, for example. Stakhiv asked if anything was unique to climate change.

Stakhiv made three suggestions for change in evaluation practices that might result in more incorporation of climate-change elements. These are (1) a return to multi-objective planning and varying the discount rate for nonvendible outputs; (2) a return to evaluation at the watershed scale as opposed to site-specific water resources project economic justification, so as to enhance overall systems objectives (e.g., river basin planning); and (3) minor changes to the environmental account of P&G.

Also cited by Stakhiv as important to planning is the proper baseline by which to measure incremental impact. For example, a Lake Erie dissolved oxygen (DO) impact study used DO versus time projection to serve as a basis for impact assessment. What was also needed was an estimation of the baseline most probable future scenario, one that might include the possibility that people would adapt. While the physical effects of certain actions might be the same no matter what the baseline, estimation of impacts (versus what would happen otherwise) will vary for different baseline projections.

The benign aspect of climate change raises the issue of risk analysis. The economic decision framework may result in construction of projects with a lower reliability with the public asked to accept the risk. Water managers will use tactical and contingency measures to supplement total supplies as needed, although this process may not be as reliable as implementation of plans with long-range vision. However, while public and private sectors may be able to respond to changed conditions, the ecological system (e.g., aquatic communities, wetlands, etc.) is in a less favorable condition to respond.

Some regions may find that climate-change inputs may indeed be very germane to the planning and management process. The Great Lakes were subjected to near-record low lake levels in the mid-1960s and record high lake levels in the mid-1980s. These conditions are likely to encompass the statistically defined boundaries for lake-level fluctuations in the foreseeable future. There is a critical link between climate and likelihood of extreme lake levels. The International Joint Commission (IJC) study of water-level changes in the Great Lakes is considering the implications of possible climate change. As Benjamin Hobbs discussed in his paper "Climate Change and Management of Water Levels in the Great Lakes," several other factors add to the need to include climate-change considerations. The multi-decade time horizon considered in this planning effort and the time frame of anticipated climate change are the same. Climate-change information is also being collected now because of a decision to be made soon on a $1 billion lake-level control mechanism--a 100-year investment to be built in one stage rather than in a series of steps. In this study, a cascade of models will explore explicit assumptions regarding climate change and lake-level fluctuations.

A multi-objective comprehensive approach to river (in this case lake) basin planning is being used in the Great Lakes study. The approach, not bound by P&G, can integrate a large portion of the range of anticipated physical consequences of climate change. The multi-objective approach will be used to screen measures in the early stages of plan formulation; emergent measures will be subjected to a more detailed impact analysis and to multi-criteria evaluations before being presented to a public forum. The analysis will show tradeoffs and clarification of values that will help the IJC make better decisions. Any IJC decision will be contentious.

Most agree that climate change will not have a dramatic onset. However, in an effort to anticipate climate change in one basin rather than simply muddling through, a study funded by the Corps' Institute for Water Resources is focusing on the issue of water supply and climate change in the Potomac River basin. The study should reveal much about the basin and climate change and provide a better environment for making good decisions. According to Roland Steiner in his paper "Framework for Analyzing Water Resource Management Under Climate Uncertainty, the Potomac River Basin," the Potomac River basin was thought to be a highly studied system 30 years ago. However, he advocated a need for a better understanding. The basin is experiencing a growing water demand that climate change will only exacerbate. The study will focus on bringing together analytic models to look at climate-change scenarios and impacts in the basin. A sequence (cascade) of models will look at various parts of the system; e.g., water availability, use, and decision-making. The GCMs will provide the forcing function that will look at how the overall system responds to climate uncertainty (changing means and changing variability).

The use of a cascade of models to understand a river basin's response to climate-change scenarios started a di^^ussion on the validity of those models, especially of cascade a stochastic models. A concern is the supe nposition of a level of uncertainty on another level of uncertainty. Some participants felt that substance can disappear in the process. While model results may be supported by authorities and decision-makers, the models and the results may not increase understanding of the system and its processes. Most still believe in some level of modeling, and that models are getting better. However, do our models adequately represent complex systems; do we have adequate long-term data to properly calibrate models; and can models, with inherent uncertainty built in, be used in a sequential process and produce reliable outputs? Clearly, many now believe that GCMs are not sufficiently precise or reliable to serve as a basis for making better decisions today for water resources development and management.

Climatologists asked whether there is a message from this conference. Is there no need to include climate change? And how does one know? Climatologists are trying to say that surprises may occur. Their mission is to bring information forward. There is a blank page between climate models and management of water resources. Good impacts research is needed to build that bridge. In some regions, future climate change may be outside present experiences. Thus, it is worth while to input data to test models, such as for the Great Lakes.

Some participants countered by asking what models can provide when they are not giving us useful information now. Further, water planners need to know other things that affect their plans and decisions. Climatologists respond that GCMs, which are a primary motivating force, need to be used. Global warming alone is not enough. All the GCMs provide similar warming predictions.

Management of many U.S. water resources systems is stressed today. Many question system outputs. In some cases, better information is needed such as how ecosystems respond to varying outputs. In other cases, institutional problems are paramount. Better management of these resources whether under drought or over the entire hydrologic spectrum should provide a basis--a process--that will enable that basin to face any looming changes in climate. Considering climate change may force us to deal with any tradeoffs in a more forgiving time than after climate change.

Several things seem clear. First there is a growing consensus that global warming will lead to significant change. This climate change will inevitably influence the world's water resources, although how much and in what direction is still highly uncertain. Climate modelers believe enough evidence is available to warrant more attention by water planners and managers. Water planners and managers, however, do not see how they can responsibly plan for long-term uncertain future conditions--particularly when the current trends are toward short-term, limited responses to historical climate variability. They believe that water resources planning is inherently involved in managing hydrologic variability and that the experiences and planning technology will enable an adequate response to a gradually changing climate. Both sides are correct and both sides are wrong. Debates such as this one are useful. Out of debates and discussion will come, we hope, a better balance between long-term and short-term planning.

CLIMATE CHANGE AND MANAGEMENT OF WATER LEVELS IN THE GREAT LAKES

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ABSTRACT

The International Joint Commission (IJC) is currently embarked on Phase II of the Lake Levels Reference Study. The charge given to the study is to investigate a range of alternatives, or "measures," for controlling and mitigating the effects of extreme levels of the Great Lakes. The measures range from land-use controls to protective structures and flow regulation. The comparison of measures must consider a wide range of social, economic, biological, and physical impacts and how they affect each interest group. The many linkages within the Great Lakes system must also be recognized. This suggests that a systems approach to estimating impacts of alternative measures and to evaluating tradeoffs is desirable.

A critical link is between climate and the likelihood of extreme lake levels. Should evaporation rates increase, as is predicted by climate-change models, the benefits of measures designed to control the effects of high lake levels could diminish, while the benefits of measures for managing low levels would increase. The multi-decade time horizon considered in this planning effort and the time frame of anticipated climate change are the same. Some investments under consideration--in particular, control structures for Lake Erie and large-scale diversions into Lake Superior--would have lifetimes stretching beyond the year 2050. Hence, it is crucial that the implications of possible climate change be considered in evaluating measures.

A systems-based approach to analyzing the risks to lake-levels management posed by climate change is proposed. Its philosophy is to link together simplified models of the hydrologic, biological, and social subsystems comprising the Great Lakes system so that the possible effects of climate change upon lake levels and, in turn, upon criteria of importance to IJC and the interest groups can be conveniently explored. A multi-attribute tradeoff method based upon successive elimination and additive value functions is proposed for the display of tradeoffs among measures and to help users articulate their preferences. The main purpose of the system is to bring together what is known already about; for example, stage-damage curves and the response of runoff to postulated climate change in one place where the linkages among the different subsystems and impacts can be accounted for. The hope is that by doing so, it would be easier to recognize the possible implications of climate change for the evaluation of measures for controlling lake levels and mitigating their effects.

INTRODUCTION

Much more research is needed to resolve the uncertainties both in atmospheric modeling and the assessment of impacts due to climatic change and variability.... In addition, we must begin to think about how to model the various linkages between society and the natural environment and subsequent feedbacks that a societal response may impose on the entire (Great Lakes) system.... This "second generation" of studies represents an exciting challenge for researchers, policy advisors, and managers (Cohen, 1989).

There have been many analyses of the possible effects of global warming upon the Great Lakes of the United States and Canada (U.S. National Climate Program Office and Canadian Climate Centre, 1989; Smith and Tirpak, 1990, summarized in Smith, 1991). Several studies have projected that if CO_2 levels double, evapotranspiration in the region would increase, causing mean lake levels to drop by 0.5 to 2.5 meters. Among the specific issues that have been identified and studied are the following:

- Direct physical effects of climate change (lake levels and ice cover, and their impacts upon shipping, shoreline land uses, and wetlands) (Croley, 1990; Hartmann, 1990a)
- Water quality (pollution concentrations, dissolved oxygen, lake thermal structure, and eutrophication) (Blumberg and Di Toro, 1990; McCormick, 1990; Schertzer and Sawchuk, 1990)
- Aquatic ecology and fisheries (effects of changes in water levels, wetlands, and water quality upon ecosystem productivity and stability and fishery composition and abundance) (Hill and Magnuson, 1990; Magnuson et al., 1990)
- Energy (demands and hydropower production) (Sanderson, 1987)
- Navigation (shipping costs and dredging requirements) (Keith et al., 1989)
- Socioeconomic (population inmigration, economic growth, recreational uses) (Smith and Tirpak, 1990)
- Policy (increasing conflicts among different interests concerning level and flow regulation, diversions, consumptive uses, pollution control; development of institutions for management of those conflicts; the need to consider and manage the large uncertainties that exist about potential physical and socioeconomic impacts and adjustments) (Hartmann, 1990b)

A number of individual issues have been studied in some depth, and sophisticated models have been developed for many of the physical effects (e.g., the detailed hydrologic models developed by the Great Lakes Environmental Research Laboratory (GLERL); see Croley and Hartmann, 1986; Croley, 1990).

Despite--or perhaps because of--these myriad efforts, there is a need for an integrated modeling framework that can bring together these disparate issues and capture the interactions between physical effects, socioeconomic responses, and management. To be useful for policy-making and project evaluation, such an evaluation framework should have the following characteristics:

- It should be comprehensive in that it considers the important interactions and linkages among climatic, hydrologic, ecological, physical, social, economic, and policy systems.
- It should produce a set of indicators or performance attributes that are meaningful and solidly grounded in theory and th[illegible] [illegible]e the major concerns of policy-makers (see the discussion by

Koonce (1990) of the use of indicators to assess the effect of management upon the ecological health of the Great Lakes). Such indicators should be in a form usable by multi-criteria decision-making methods so that decision-makers can consider and evaluate tradeoffs among different policies (Hobbs et al., 1989). An example of such a tradeoff might be between mean hydropower production (measured in megawatt-hours) and average annual shoreline erosion damage (in hectares, linear meters, or dollars).

- It should allow policy-makers to conveniently explore the general implications of different assumptions concerning climate change, the response of physical and socioeconomic systems, and the effectiveness of alternative management measures. Because of the gross uncertainty surrounding many of these issues (Fiering and Matalas, 1990; Moss and Lins, 1989; Rogers, 1990), the framework should be flexible so that extensive sensitivity analyses are possible. Risks in the system and risk preferences of decision-makers should, to the extent possible, be modeled.

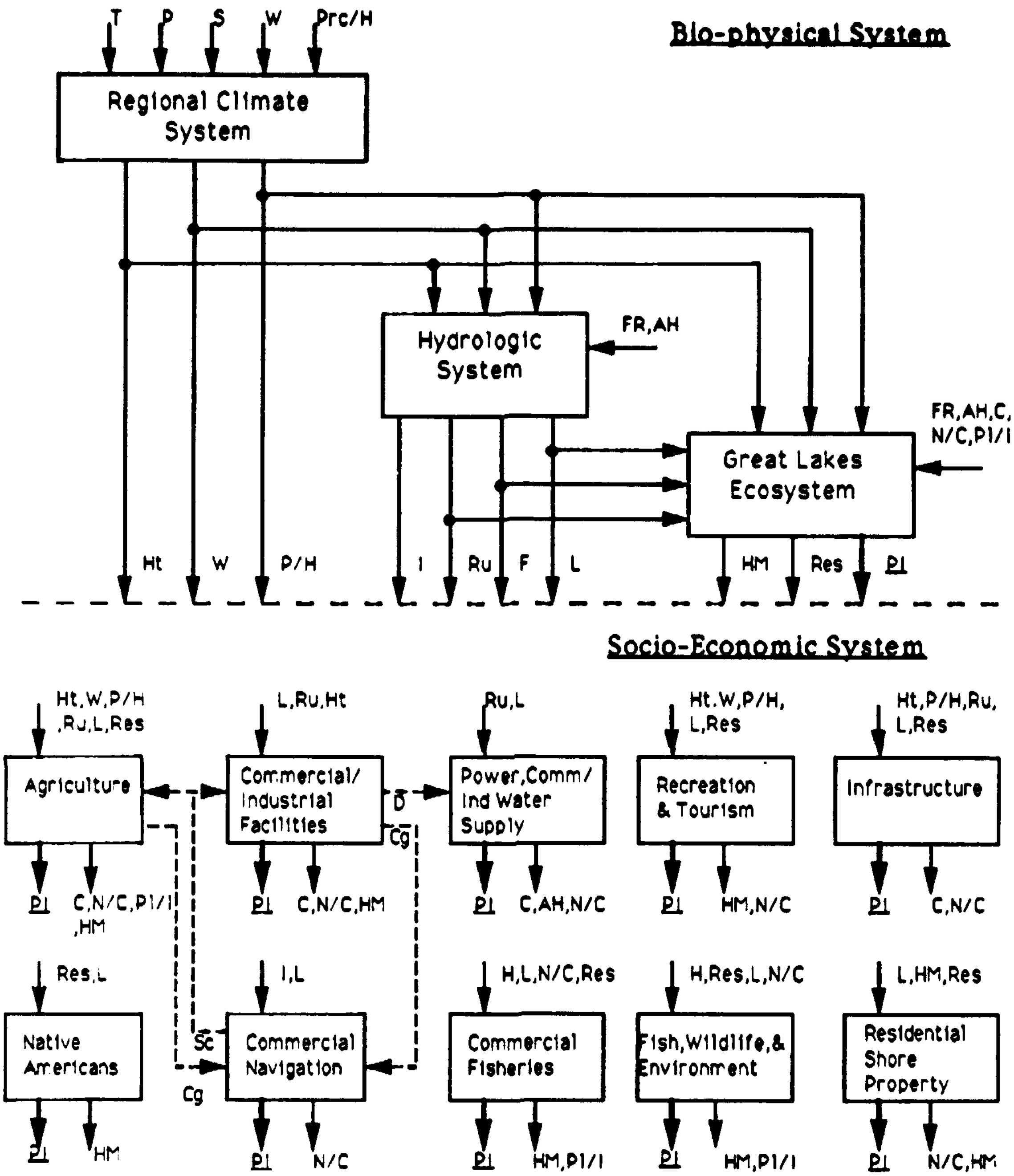
- Where there is uncertainty or disagreement about important processes, the system should be designed so that alternative judgments can be easily incorporated and their implications compared. Likewise, the system should facilitate the incorporation of alternative value judgments concerning the importance of different evaluation criteria. This could facilitate discussion and either consensus or a fuller understanding of the reasons for disagreement (Holling, 1979; Brown, 1984).

- It should rely on existing models and data sets to the extent feasible, in order to avoid duplication of effort. However, in order to meet the requirement for flexibility and comprehensiveness, it may be necessary to, for example, simplify those models or create "models of models" in which the input-output relationships of a complex model are summarized by relatively simple functions estimated by statistical analysis.

In this paper, we summarize such a framework that is presently under development. The immediate purpose of the framework is to provide information relevant to decisions concerning the management of fluctuations in the levels of the Great Lakes and their impacts. Such decisions are now being considered by the IJC's Lake Levels Reference Study, Phase II. Should we be able to demonstrate that the framework would be useful in this context, we hope to generalize it so that it could be used for exploring the implications of climate change for other Great Lakes management problems.

Kleme ') has questioned the value of detailed assessments of the impact of climate change upon water resources whe re so many fundamental uncertainties concerning climate change and the hydrologic system's response to it. akes the point that when a series of models are assembled, as in Figure 1, and there are large uncertainties in each, the resulting probability density of the output can be so flat and broad as to be useless for decision-making. We feel strongly, however, that such modeling exercises can be useful. If decisions are being made now whose present worth of benefits and costs is significantly affected by the prospect of climate change, then it is better to make explicit assumptions and to trace the implications of those assumptions through models rather than to base decisions solely upon subjective judgment and back-of-the-envelope calculations. As Klemes (1991) emphasizes, it is important to recognize what we do not know; models can help us do that by pointing out the wide range of possible outcomes that result from alternative plausible inputs. These outcomes can then be analyzed using a framework, such as decision trees (Fiering and Rogers, in press), that explicitly accounts for uncertainty and the value of flexibility.

The next section briefly reviews the IJC Lake Levels Reference Study and how it plans to consider climate change. Then in Section 3, an overview of the comprehensive modeling framework that we propose is given. Sections 4 and 5 then describe particular components of that framework: the physical/biological models and the categories of impacts considered. The future development of the framework is discussed in Section 6.



Definitions

AH : Artificial Heat
C : Water Consumption
Cg : Cargo Demand
D : Power Demand
Dr : Dredging
HM : Habitat Modification
Ht : Heat (Water Temp)
I : Ice Cover
L : Lake Level
N/C : Nutrient Loading
P : Air Pressure
Pl/I : Planting/Introduction
P/H : Precipitation/Humidity
Res : Resource Use
Ru : Runoff
S : Solar Radiation
SM : Soil Moisture
Sc : Shipping Costs
T : Air Temp
W : Wind

Figure 1. **Schematic of the lake levels impact assessment framework**

THE IJC LAKE LEVELS REFERENCE STUDY AND CLIMATE CHANGE

The study's purpose is to "examine and report upon methods of alleviating the adverse consequences of fluctuating water levels in the Great Lakes-St. Lawrence River Basin" (U.S. Department of State and Canadian Department of External Affairs, 1986). The study was motivated by record-high lake levels in the mid-1980s that caused extensive property damage and, to a lesser extent, low water levels in the early 1960s that adversely impacted hydropower production and shipping (Horvath et al., 1989). The interim report from the initial phase of the study was issued in 1989 (IJC, 1989a). After a public review period, the commission in 1990 began a second phase of the study. This phase includes the determination of the socioeconomic costs and benefits of alternative land-use and shoreline management practices and a comparison of those with the costs and benefits of lake regulation schemes.

"Costs" and "benefits" are to be interpreted in a multi-dimensional or multi-criteria sense. No single figure of merit will be used to compare the measures. Instead, the following impacts, organized by categories of water use, will be tallied separately: infrastructure impacts (including domestic water supply, sanitation, and other public facilities); commercial navigation; electric power; industrial and commercial water supply and flood/erosion damages; agriculture; residential flood and erosion damages; fish, wildlife, and other environmental aspects; commercial fisheries; recreation; and native North Americans. Section 5 discusses the categories in more detail. These impacts will be further disaggregated by region (Donahue and Slivitzky, 1991). After a prescreening process that will narrow the number of measures considered in IJC (1989b) down to 15 to 20, the surviving measures will be evaluated using several criteria. These might include some or all of the following criteria identified by the Study Board (IJC Working Committee 4, 1991):

- Economic sustainability
- Ecosystem integrity
- Social desirability
- Implementability
- Equitability

The Phase II study is considering a wide range of measures to alleviate the impacts of fluctuating, extreme high, and extreme low water levels. The measures can generally be classified into the following groups: operation and design of structures to regulate water levels; land-use regulation; land-use incentives, including taxes and subsidies; shore-protection alternatives; and adaptive practices, including emergency response measures.

Many of the measures are relatively flexible ones that can be implemented or altered as circumstances change. These include operating policies for existing flow-regulation works that control Lakes Superior and Ontario and emergency actions to be taken during crisis conditions. Should climate change cause lake levels to fall significantly, these actions could be altered at little cost. Consequently, the merits of implementing such measures in the near future should not be affected by the prospect of significant climate warming in the 21st century.

However, there are other, more long-lived measures whose benefits and costs could be greatly affected by climate change. These include construction of additional structures to regulate flows and restrictions on development in flood-prone areas. In the case of measures designed to deal with the effects of high lake levels, global warming might decrease their benefits because such levels might occur less frequently or warming might actually enhance their benefits because the lakes would be ice-free longer, making shorelines vulnerable during severe winter storms. In contrast, the benefits of measures that would prevent or ameliorate the effects of low levels might be increased. Unfortunately, the effects of climate change are highly uncertain, which implies that planning should explicitly focus on the sensitivity of the system to climate change. Planning should consider a wider range of flexible alternatives that would lower the vulnerability of the system and allow it to adapt as new knowledge becomes available (Cohen, 1989; Hartmann, 1990b; Fiering and Matalas, 1990; Fiering and Rogers, in press; Riebsame, 1990).

However, Rogers (1991) argues that climate change that occurs beyond, say, 30 or 40 years in the future has little impact upon decisions concerning water investments made today. His analysis focuses on decisions concerning the size and timing of independent increments to water supply capacity. He concludes correctly that uncertainties in, for instance, water demands or supplies well in the future make little difference in scheduling and sizing the next increment. This is true primarily because changes in conditions far into the future impact decisions concerning increments at that time much more than they affect the increment being considered today. However, the regulation of Great Lakes levels is a different type of decision. One important set of alternatives under consideration would install, once and for all, regulatory structures at the outlet of Lake Erie. Such an investment would not just be an increment to be followed by later increases in capacity. Rather, the system installed now would probably be the same as the system in place in the mid-21st century. If climate change would significantly affect the present worth of such a structure's benefits and costs, climate change could indeed affect a decision made today.

IJC recognizes that the implications of possible climate change could be important, and has directed that the study consider them. Annex C of the Phase I report summarized possible effects of climate change upon the Great Lakes. A workshop was conducted in June 1991 in which methods for incorporating climate change in Phase II were reviewed and an approach decided upon (IJC Task Group 2, 1991). First, the Canadian Climate Centre general circulation model will be used to generate two 10-year daily time series of climatological variables, one assuming present-day levels of CO_2, and another based upon a doubling of CO_2 levels. Then the Great Lakes Environmental Research Laboratory hydrologic response model (Croley and Hartmann, 1986; Croley, 1990) will be used to translate those time-series into net basin supplies. Finally, those supplies will be used in a U.S. Army Corps of Engineers routing model to generate lake levels. No probabilities will be attached to the global warming scenario; consequently, a formal decision tree analysis along the lines recommended by Fiering and Rogers (in press) or Patwardhan and Small (1990) cannot be conducted. Instead, this information will be used as a sensitivity analysis, in the spirit of Liebetrau and Scott (1991).

THE PROPOSED FRAMEWORK

Our modeling framework is designed to serve the needs of planning efforts such as the Lake Levels Reference Study. The framework consists of two basic parts:

- An impact estimation model
- A multi-criteria decision model

The former consists of models of physical, biological, and social processes whose purpose is to estimate the consequences of measures for controlling or mitigating the impacts of fluctuating lake levels. These consequences are expressed in terms of criteria by which the measures are to be evaluated. The multi-criteria model's purpose is to help users to (1) better understand the tradeoffs among the criteria and (2) articulate their preferences in a consistent and replicable manner (Hobbs et al., 1989).

Because of the timing of our project, the impact estimation model will not be developed in time to provide input to the Lake Levels Reference Study. A prototype of that model for Lake Erie alone is to be completed by mid-1992. However, the multi-attribute decision model will be used by Working Committee 4 of the study as part of its evaluation of measures during the spring and summer of 1992. The intention is to develop and integrate both models in time for possible followup planning studies.

Figure 1 shows that, as in most regional assessments of the impact of climate change, the process models are linked in the following way (Liebetrau and Scott, 1991; Cohen, 1990; DeAngelis and Cushman, 1990):

- First, the output of runs of alternative GCMs under alternative assumptions are summarized in the form of climatological scenarios.

- Then, so-called "first-order" effects on natural resources are calculated using hydrodynamic and other physical process models whose outputs (lake levels, temperatures, stratification, etc.) can be fed into water chemistry and ecological models.

- The outputs of the natural resources models then directly impact economic agents, yielding "second-order" effects. These impacts can be grouped into impacts upon production functions (e.g., fewer crops are produced with a given input of labor, capital, and land due to decreased rainfall, or more fish are harvested with a given set of inputs due to greater lake productivity), direct impacts upon consumer welfare (e.g., enjoyment of lakefront property increases because there is more extensive beach), and impacts upon durable assets (less frequent flooding results in less damage to land and property).

- Finally, the economic agents who experience second-order effects in turn attempt to mitigate these effects by changing market behavior or location or by other resource-management actions. These are termed "third-order" effects.

But as Figure 1 also reveals, the flow of the system is not necessarily just in one direction; feedbacks can occur. For instance, lower lake levels will increase shipping costs, which in turn may motivate increased dredging. Dredging activities and dredged materials disposal might then feed back to the ecological system in the form of greater pollution. It is important to identify such feedbacks because if they are important, they could complicate sensitivity analysis methods that assume that such feedback is absent (Liebetrau and Scott, 1991).

Each of these models, some of which are discussed further below, also provide estimates of the economic, social, and environmental performance of the measures that are assumed to be in place under the climate assumptions made. In our framework, these performance criteria are then fed into a multi-criteria analysis. This analysis has two aims: to display information and to facilitate the expression of value judgments.

The information displayed consists of tradeoffs among criteria. Multi-criteria display methods attempt to show in a succinct and clear manner how each measure (or combination of measures) performs on each criteria. Examples include XY plots (if there are few criteria); factor profiles; *Consumer Reports*-type tabular displays; and tabulated descriptions, such as the account tables of the U.S. Principles and Guidelines for federal water resources planning. A combination of methods, consisting of a simple display accompanied by a detailed table, may be most useful.

Two types of information will be displayed: impacts on individual water uses (the IJC impact categories listed in Section 2) and criteria, such as net economic benefits or economic sustainability, which cross interest boundaries.

Display methods may provide all the information that is needed for negotiation and less formal decision-making processes--or that information can be the starting point for an analytical multi-criteria decision analysis. There are many approaches to such an analysis. The goal of each is to help the users to make their preferences more coherent and give appropriate consideration to all criteria and uncertainties. Just a few examples of such methods include exclusionary screening; additive value functions (of which the Phase I Lake Levels Study Evaluation Framework is an example [IJC, 1989c]); goal programming; and so-called "outranking" methods such as ELECTRE (Chankong and Haimes, 1983). These methods can be used to help build consensus and clarify differences of opinion by allowing all interests to do their own evaluations and make their preferences explicit (Brown, 1984, 1990).

In experiments involving Corps of Engineers planners, we found that a simple additive value function is relatively well accepted, least likely to be misunderstood, and, if carefully applied, no less likely than other methods to yield choices that are consistent with the decision-makers' values (Hobbs, Chankong et al., in press). Therefore, if a user wishes to apply a single analytical multi-criteria decision method, we recommend the additive approach. This method has been used successfully in several water resources planning studies (Brown, 1984, 1990).

However, a more satisfactory approach might be to use several methods in sequence. First, measures could be eliminated using the concept of dominance (options that are no better in each criterion than any other option are dropped) and screens based on legal and policy criteria. Then the surviving measures could be evaluated by each of the interest groups using successive elimination (Kirkwood and Sarin, 1985). Successive elimination uses partial information on preferences (such as "the weight for navigation impacts should be no more than the weight for wetland effects" or "the performance of measure X on criterion A is between 0.2 and 0.4") to rule out some options. If an insufficient number of measures are eliminated, users would provide more information. The advantage of this process is that it forces users to be no more precise than is necessary to make a decision, a distinct advantage over methods that ask for the exact values of weights and other parameters. Should there remain many viable measures, or if the interests disagree over which should be eliminated, users could then be asked for specific additive value functions in the manner of Brown (1984, 1990).

Because of the gross uncertainties in every level of the analysis, a comparison of measures based on a single set of assumptions would be foolhardy and misleading. Sensitivity analysis is a necessity (Liebetrau and Scott, 1991; Riebsame, 1990), but not sufficient. We agree with Fiering and Rogers (in press) that much insight is to be gained by analyzing management decisions under climate uncertainty using the tools of decision trees and Bayesian analysis. Such an approach allows for explicit quantification of the worth of information and the value of flexible strategies that leave options open.

We propose that decision trees be used to quantify the flexibility of different measures. Flexibility is the ability of a system to adapt its design or operation to changing conditions. We propose that flexibility be quantified as the difference between a system's performance obtained using a single forecast of climate and other conditions (traditional engineering economic analysis) and its expected performance calculated using decision trees that consider the entire range of uncertainties and possible adaptations. Flexible alternatives enhance the system's performance under uncertainty and, thus, lead to higher flexibility. We have successfully used this approach to compare emissions control alternatives for electric utilities (Hobbs, Honious, and Bluestein, in press).

In the following sections, we further discuss the biophysical models, interest groups, and criteria that will be included in our framework. At this time, the framework is in the prototype phase. Only models for Lake Erie have been incorporated, and many of the component relationships have not been finalized. Future work will emphasize demonstration of the framework for Lake Erie followed by extension of the framework to encompass all of the Great Lakes.

BIOPHYSICAL MODELS

Following the structure in Figure 1, we break down the biophysical process models of our framework into three submodels: climate, hydrologic, and ecological.

Climate Model

Our framework embodies the approach used by Croley (1990) and Hartmann (1990a) at the Great Lakes Environmental Research Laboratory. They have combined general circulation models with GLERL's Great Lakes hydrologic response models (Croley and Hartmann, 1986).

GCMs have been used to develop possible scenarios of changes in precipitation, air temperature, humidity, insolation, and wind on a monthly basis. In their studies, Croley and Hartmann have compared three different GCMs under a double CO_2 scenario. These models have been developed by the Goddard Institute of Space Studies (GISS) Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU).

Because of low model resolution and imperfect representation of climate processes, the output from GCMs, especially on a regional scale, is uncertain. (The Canadian GCM that has been adopted for the IJC Lake Levels study has a finer resolution than the three models just cited, which may bolster confidence in its scenarios.) This is illustrated by the discrepancies in air temperature and precipitation results of the three models under the double CO_2 scenario. GFDL predicts a 5.7°C increase in air temperature over Lake Erie compared to a 3.4°C increase yielded by the OSU model. Their precipitation predictions diverge even more. For that variable, GISS gives a 6 percent decrease while OSU predicts a 6 percent increase. Adding to that uncertainty is the inability of the GCMs to model local phenomena, such as the snowbelts on the eastern coasts of all the lakes.

Furthermore, the frequency and intensity of extreme events cannot be reliably accounted for in these models. It is this type of event, such as seiches, that governs the amount of flooding damage. For example, since seiches on Lake Erie can reach 3 meters and waves 2 meters, a change of a fraction of a meter in the average level of the lake due to climate change might or might not make a detectable difference in damage (Changnon, 1989).

Hydrologic Response Model (HRM)

Croley and Hartmann used the output of the three GCMs just mentioned to create climate scenarios for use in GLERL's HRM. They did this by running HRM simulations using daily climate and hydrologic data for the period 1951 to 1980, adjusted by the changes predicted by the GCMs. For example, if model X predicted a 10 percent decrease in precipitation for a given month, then the historical data for that month would be multiplied by 0.9 before being fed into the HRM. Similar adjustments were performed for temperature, specific humidity, insolation, and wind speeds.

The HRM as originally developed by Quinn (1978) was essentially a reservoir routing model simulating water level and flow in the unregulated Great Lakes (Huron-Michigan, St. Clair, and Erie). The model was later elaborated upon to include runoff sub-models for 121 basins and lake evaporation (Croley, 1983, 1989; Croley and Hartmann, 1984, 1986).

Because of the computational effort required to use the HRM, our prototype presently simulates its input-output relationship by a regression model that relates climate inputs to water levels in the unregulated lakes and water temperature. However, a more sophisticated model will be required for flow routing to simulate the impact of existing control structures on Lakes Superior and Ontario and the possibility of new structures for the other lakes. Such a model would strike a balance between the need to understand the relationship of control measures to lake levels, and the need for quick execution times.

For the moment, however, our framework incorporates a simple model of the effects of each proposed structure upon Lake Erie's water level. These models are for regulation plans 50N, 25N, 15S, and 6L. The latter three plans were originally developed for the 1981 Lake Erie Water Level Study (IJC, 1981a). The plans consist of the construction of control structures on the Niagara River to increase the outflow from Lake Erie compared to the present natural outflow. The numbers in the plan names represent a nominal increase in capacity in thousands of cubic feet per second. The trailing letters represent the proposed location of the control structures; these are the Niagara River, Black Rock-Squaw Island diversion, and Black Rock Canal for N, S, and L, respectively.

Ecological Models

There has not yet been a comprehensive study linking hydrologic and climate variables with biological processes in the Great Lakes. However, there have been many specialized studies that can be drawn upon for this analysis. The specific ecological processes that are of interest in this paper are climate-affected processes that can be controlled or influenced by lake-levels management measures. Studies of particular interest include those of fish populations, wetlands area and quality, sediment pollution, and lake trophic and toxic status. Some of these studies are reviewed below. From these studies, we will attempt to abstract important relationships between hydrologic and climate variables and ecological impacts for use in our framework.

Fish population dynamics have been the focus of much work, driven as much by fishery concerns as by environmental concerns. Several aspects of fish population dynamics are important to consider in climate-change analyses. Among these are the effects of warmer temperatures upon metabolic processes and the potential for warmer habitat fish to invade and upset the balance of the food chain (Mandrak, 1989). Because lake-levels management is not anticipated to affect those changes, we do not attempt to model them. Instead, we focus on the question of the quality and size of thermal habitat for fish (Magnuson et al., 1990), in particular the habitat for cold-water fish in the central basin of Lake Erie.

As has been often noted (e.g., Blumberg and DiToro, 1990), the level of Lake Erie may affect the amount and quality of that habitat because the hypolimnion is relatively thin and subject to variable rates of oxygen depletion. Historically, this cold-water habitat supported large fish populations. The annual harvest of the blue-pike, *Stizostedion vitreum glaucum*, ranged from 3,000 to 12,000 metric tons from 1915 until the population collapsed in 1958 (Leach and Nepszy, 1976). Although a combination of factors (over-fishing, genetic introgression, and habitat destruction) contributed to the collapse, hypolimnetic oxygen depletion in the central basin was a critical catalytic factor (Regier et al., 1969). Subsequent periods of anoxia have removed this valuable habitat for other cold-water species and associated benthos, and the loss of the production potential for fish harvest has led to greater stress on other species (Regier and Hartman, 1973). Restoration of this habitat is thus a necessary step to achieve a major goal of the Great Lakes Water Quality Agreement: the restoration of the integrity of the Lake Erie ecosystem.

Two aspects of wetlands dynamics are important: (1) area and (2) biological activity (Manny, 1984). The amount of wetland area is a function of lake levels. Long-term drops in lake levels could reduce wetland extent due to unsuitable offshore substrates and steep offshore dropoffs.

Wetlands depend upon both the mean and variance of lake levels because of the importance of intermittent flooding to wetland preservation. Because the relationship between levels and wetland extent and productivity is poorly understood, any model of the effect of levels on wetlands will by necessity rely to some degree upon expert judgment. The framework is designed to allow such judgment to be conveniently incorporated and quickly changed in order to evaluate sensitivities.

The final ecological impact we are including in the framework is that of possible increased dredging due to changed lake levels. Because the effects of dredging and materials disposal upon pollutant loadings and, ultimately, ecological and human health is not fully understood, we will simply use volume of dredged materials as a performance criterion.

INTEREST GROUPS

Given the diversity of the peoples and organizations that derive benefit from the Great Lakes, it is important to give *close consideration of the positions taken by interests, how they respond to changing conditions, and how they interact with governments* (IJC, 1989a).

In the study, as explained in Section 2, the IJC developed a framework of *interest groups* to organize their evaluation of measures to alleviate the adverse effects of extreme water levels. This framework has further evolved into the concept of *impact categories*. The impact categories place more emphasis on the nature or mechanism of impacts due to fluctuating lake levels, while somewhat deemphasizing the political nature of interest groups.

Section 2 listed those impact categories, which are 10 in number. We describe them further below, while discussing the models we have developed thus far of those impacts for Lake Erie. We consider only those impacts that would be affected by the measures considered in the study. Thus, for instance, we disregard the effects of lake warming upon sea lamprey populations because even though they will be affected by climate change, the measures considered will not alter those impacts.

Most of the models in our framework are statistical relationships based on data from previous studies. Although simple, this information is an improvement upon the subjective approach in the Phase I study in which experts used a scale of -3 to +3 to rate whether a criterion would be made worse or better off because of a particular measure. Our study can be viewed as an effort to replace or supplement subjective judgment with a system model with explicit assumptions.

The first impact category covers effects upon water supply and sanitation utilities, who are concerned with the costs imposed upon them by extreme water levels. These costs would include the expense of adapting facilities to lower or higher average levels and of repairing flooding and erosion damages.

The second category is commercial navigation. Many industries depend on Great Lakes shipping for domestic and international transportation. Low lake levels reduce channel depths, requiring more dredging and/or lighter ship loadings. Both responses increase costs. On the other hand, climate warming would lengthen the shipping season. In our framework, shipping impacts as a function of lake levels are derived by a regression analysis of the output of the model of Keith et al. (1989). That model considers changes in shipping cost, shipping capacity, and dredging costs as a result of changes in mean annual water level and ice cover.

Electric utilities derive benefit from the lakes by producing hydropower, the third impact category. Their primary concern with lake levels is the lost head and flow through their hydropower facilities; to replace this power, energy conservation programs and expensive thermal generation facilities are needed. Those facilities could, in turn, increase the demand for cooling water from the lakes. The 1981 Lake Erie Water Level Study (IJC, 1981b) provided data that allowed us to statistically relate losses of hydropower from Niagara River plants and changes in the level of Lake Erie.

Industrial and commercial facilities on lake shorelines, the fourth category, are subject to flood and erosion damage. This group is also concerned with access to water supplies that, if lake levels drop significantly, might require relocation of water intakes. The fifth category, agricultural impacts, also includes flood and erosion effects. In addition, high lake levels also necessitate increased dike maintenance and construction, while low levels increase pumping costs for irrigation. Further, a warmer climate could increase demands for irrigation water, leading indirectly to lower lake levels.

Residential shore property impacts, the sixth category, include flood and erosion damages to private land, structures, and facilities. We presently quantify dollar damages to Lake Erie riparians through a regression analysis of stage damage curves from the 1981 Lake Erie Water Level Study (IJC, 1981c).

As mentioned in Section 4.3, fish, wildlife, and other environmental impacts, the seventh category, can be further divided into effects upon wetlands quality and quantity, sediment pollution, and lake trophic and toxic status. The models we are developing for those impacts are discussed there.

Commercial fisheries, the eighth impact category, are concerned with fish population changes due to extreme levels and alterations in water temperature. Another concern is with the impacts of flooding and erosion on shore-side facilities.

The ninth category, recreation impacts, includes effects upon recreational boaters, beach users, recreational fishing, and hunters. Boaters are affected by boat and harbor damages due to low levels. Beach visitors will have more beach to visit for longer periods of time if lake levels drop and the climate warms. Hunters might be affected by loss of wetland habitat of their prey. We have developed a regression model that relates the value of beach use opportunities to changes in water level. This value considers willingness of visitors to pay entrance fees and the expense of travel. Another model relates value of lost boating days due to insufficient channel depths to changes in lake levels. The value of boating days reflects the rate of return on investments of comparably sized boats in the for-hire boating sector and the absence of impediments to boating. Both models are based on the 1981 Lake Erie study (IJC, 1981c).

The tenth category includes impacts upon native North Americans, who are concerned about their ability to maintain cultural activities closely tied to the environment. Possible violations of treaty and land rights by some measures must also be recognized.

CONCLUSIONS

The first purpose of the proposed framework is to facilitate better understanding of the systemwide effects of measures for controlling and ameliorating the effects of fluctuating Great Lakes levels under climate change. The second purpose is to encourage careful consideration of tradeoffs among the many important evaluation criteria. At present, we are incorporating models for Lake Erie in the framework; eventually, the framework will encompass the entire Great Lakes system.

Ultimately, we hope that the framework can be expanded so that it could be useful in analyzing the interaction of climate change with other Great Lakes management problems. These include water quality planning, fisheries management, and policies toward water diversion and consumption.

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WATER RESOURCES PLANNING AND MANAGEMENT UNDER CLIMATE UNCERTAINTY

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ABSTRACT

A selective overview is presented of U.S. federal water resources planning and management as it is practiced under contemporary climate variability. The premise of this paper is that water allocation, distribution, planning, design, operation, regulation--i.e., all of the functions that comprise water resources supply management as it has evolved during the past 25 years, together with the range of complementary demand management tools and measures--comprise virtually the same set as that which should serve as the basis of an adaptive response strategy to postulated climate change. The diverse programs, procedures, and authorities of the Corps of Engineers are used to illustrate how the accumulation of numerous small changes in the present range of water resources management practices and procedures increases the flexibility for adaptation to current climate uncertainty and serves as a precursor to future possible responses within an ill-defined, changing climatic regime.

Impediments to more efficient and effective adaptation to perceived climatic changes are discussed, foremost among which is the absence of comprehensive, river basin scale planning and management that is commensurate with the anticipated subcontinental and regional scale of climatic and hydrologic changes. There is also a need to develop more uniform approaches to the analysis and evaluation of climate change uncertainty for actions that are undertaken by decision makers today. Although most efforts are of dubious value to practicing water managers, great progress can be made in assessing the hydrologic and ecosystem vulnerability and water management susceptibility at the watershed and river basin scale, even if project-level analysis cannot be accomplished for at least another decade.

Introduction

The impacts of potential climate change caused by global warming on water resources management has received considerable scrutiny during the past decade, resulting in countless research papers and culminating in two comprehensive and authoritative surveys, in the form of reports of the U.N. Intergovernmental Panel on Climate Change (IPCC, 1990a, b, c) and the report of the U.S. National Academy of Sciences on the "Policy Implications of Greenhouse Warming" (NAS, 1992). Increasingly, while large-scale general circulation modeling (GCM) evidence appears to support future global warming through anthropogenic additions of greenhouse gases into the atmosphere, it is not yet possible to predict either the regional incidence, timing, and magnitude of the physical hydrologic effects associated with global warming, such as precipitation and runoff, or the all-important inter- and intra-annual variability of climate. The transformation of primary physical effects into water resources management impacts (availability, use, distribution, operation), and then to socioeconomic and related environmental impacts, is fraught with a hierarchy of cascading uncertainty. This adds at least an order of magnitude of more difficulty to the ultimate resolution of which response strategies are "best."

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In short, any attempt to reliably predict the impacts of global warming on water resources management has fallen far short of expectations, although numerous carelessly conceived studies have ventured into naive prediction through extrapolation, without concern for the basic validity of the GCMs or even defining the fundamental issues and questions to be answered. In this milieu of a concatenation of uncertainty, which is bound to hamper, if not paralyze, an analytical evaluation of which responses are optimal, it is difficult to prescribe a set of practical or reasonable steps, actions, and precautions that a water resources manager, decision maker, or policy analyst should consider, short of simply ignoring the problem until better information is available. Indeed, this appears to be the conclusion of the Massachusetts Water Resources Authority in a study conducted of the future Boston metropolitan water supply needs under climate change uncertainty (Kirshen and Fennessey, 1992). In reality, there is a very large gap between believing that global warming will someday result in serious adverse consequences and mobilizing policies and preparing for large investments in anticipation of this trend whose specific outcomes are highly uncertain. One of the key philosophical issues is essentially a matter of belief; i.e., should we *adapt* incrementally to the explicit signals of climate change, or should society develop an *anticipatory* strategy to ameliorate the *expected* adverse impacts of such change?

Notwithstanding the difficulties of anticipating and responding to the ill-defined impacts of global warming, particularly in its various hydrologic manifestations, *a case can be made that the water resources management community need not take any extraordinary precautions because they already practice or have at their disposal most of the measures and analytical tools that are being prescribed to anticipate or respond to the postulated adverse impacts of global warming.* And it can be argued that these contemporary management measures and strategies comprise virtually the entire set of risk cost-effective actions that ought to be initiated. That is because *they are beneficial for reasons other than climate change and, for the most part, can be justified by current evaluation criteria and normative decision rules associated with conventional benefit-cost analysis and discounting.*

This is essentially the theme and general strategy presented by the IPCC Response Strategies Working Group (IPCC, 1990c): staging a reasoned, incremental response to the reasonably foreseeable range of effects of global warming. It is worth repeating the principles that the IPCC laid out, for they are familiar to the contemporary water resources manager, albeit not always applied consistently or progressively by federal and state agencies, private utilities, or even regulatory agencies. These principles state that adaptive response strategies should be undertaken when they:

- are beneficial for other reasons and justifiable under current evaluation criteria;
- are economically efficient and cost-effective;
- serve multiple social, economic, and environmental purposes;
- are flexible and adaptable to changing circumstances and technological innovation;
- are compatible with the concept of sustainable development; and
- are technically feasible and implementable.

The IPCC analysis of response strategies gave special consideration to water resources, recognizing the essential value of water for humans and the natural environment. Listed were a number of implementable near term strategies that were worth undertaking even in the absence of climate change. These included:

- determining the flexibility and vulnerability of current hydrologic systems and water management systems;
- enhancing system-wide operation;
- enhancing scientific measurement, monitoring, knowledge, and forecasting;
- implementing water conservation measures;
- addressing escalating demand for water through proper pricing mechanisms;
- establishing institutional mechanisms to assure that water is directed to where it is most productive;
- modifying agricultural irrigation practices;

- instituting design modifications and changes in operation;
- improving flood plain management and warning and evacuation systems; and
- protecting estuarine and adjacent groundwater quality susceptible to saltwater intrusion from a potential rise in sea level.

This list of adaptive actions recommended for water resources in response to potential global warming is familiar to most water managers because it is virtually the same strategy that has been proposed since the publication of the two National Water Assessments conducted by the U.S. Water Resources Council (1968, 1978) and the path-breaking comprehensive report of the National Water Commission (1973), and followed thereafter by President Carter's Water Policy Initiatives Task Force (1979) and countless other subsequent studies, commissions, task forces, and working groups. For example, a recent evaluation of U.S. water policies and reforms thought to be needed for contemporary climate conditions was presented in a book titled *Overtapped Oasis--Reform or Revolution for Western Water* (Reisner and Bates, 1990). This book formed the basis for a recent series of influential Long's Peak workshops (U. Colorado, 1992) and most likely the basis for a sweeping review of western water policy, as called for by Title XXX of the "Reclamation Projects Authorization and Adjustments Act of 1992." It is virtually the same set of actions, reforms, and initiatives proposed as part of the "National Action Plan for Global Climate Change" proposed by the United States (U.S. Department of State, 1992) in fulfillment of their obligations to the U.N. Framework Convention on climate change.

In reality, it is difficult to think of a set of substantive actions other than the ones listed by the IPCC that could be taken by water resources managers that are specifically and exclusively designed for responses to climate change and have not been proposed or implemented or are in the process of being implemented by federal water agencies for dealing with *contemporary* problems of water scarcity and climate variability. The fact is that federal water agencies are responding quite well, albeit deliberately, to the various proposed policy reforms that have gained widespread credence and acceptance and have been codified as legislation and promulgated as agency regulations, planning procedures, design criteria, and operating rules. The deliberate nature of societal responses simply reflects the complex interplay of slowly changing social values and the difficulties of mobilizing the political process to respond in a timely manner.

The key thesis of this paper is that many of the adaptive response strategies formulated by the IPCC (1990c) and the U.S. National Academy of Sciences (1992) and other water policy commissions have actually been *derived from* actions being undertaken by a variety of federal, state, local, and private entities responsible for water management. However, these management measures are being promoted as part of a diverse set of normal business and engineering practices that are driven largely by changes in demands and conflicts among water uses and sectors. The solutions are dispersed in a myriad of legislative authorities, conventional design practices, planning procedures, operating rules, cost-sharing policies, and life-cycle project management approaches. *What is missing is the development of a coherent strategy that reaches beyond the federal water management sector and which explicitly integrates the potential effects of climate change uncertainty.* The real question, then, is whether we are able to conduct meaningful analysis of the potential effects of climate change given the poorly developed state of GCM modeling. Is the information content sustainable for making important water management decisions? Rogers (1992) thinks that water managers and planners do not need to concern themselves with changes that could occur beyond 30 or 40 years in the future. He argues that uncertainties in water demands and supplies will in the future make little difference in scheduling and sizing the next increment.

The point is that society is continuously adapting, incrementally, to a variety of changes and in many diverse ways (Goklany, 1992). It is misleading, if not incorrect, to suggest that little or nothing is being accomplished in the area of water policy reform, especially at the federal level. The policies, procedures, technologies, and practices that are being carefully integrated into the current water management philosophy serve both contemporary climate variability and rapidly changing public preferences influencing the value of water. The manner in which water resources management has evolved makes it responsive to changes in information, technology, and public preferences. These factors ensure that water resources management will be coincidentally responsive to most of the changes that may be required to adapt to the predicted slow climate change. The key policy debate is whether society should *anticipate* or *incrementally adapt* to the potential changes. *The choice of an anticipatory path has profound investment and behavioral change implications that simply cannot be supported by the climate change analyses to date. In order that this choice be better understood, substantive reforms must be introduced in the manner in which climate change impact analyses are conducted. As it stands now, they are of dubious value to decision makers.*

Change and Innovation in Federal Water Management

Despite its diminished role in building new projects, the reality is that the federal water establishment is still a significant player in water resources management. The Bureau of Reclamation (BR) and the Army Corps of Engineers (COE) together control a majority of the stored water supply in the nation's largest reservoirs. As the nation's water policies are incrementally modified through periodic legislative acts, these innovations gradually diffuse to the states, municipalities, counties, and irrigation and flood control districts that depend, at least in part, on one of the many intersecting federal programs that deal with research, management, and regulation of water and related resources (e.g., wetlands, flood plain management, flood insurance program, flood warning and evacuation systems, drought counteragency planning, water supply pricing, hydroelectric power cost recovery, water quality certification, etc.). In the foreseeable future, the Environmental Protection Agency's (EPA) regulatory program, dealing with the interaction of instream water quantity, quality, and aquatic ecology, will play an increasingly important role in a myriad of small and large decisions affecting watershed-level water resources management.

Although numerous critics have charged that change and innovation in water resources management has been relatively slow, academic literature suggests that in some areas the water resources field has been fairly quick to adapt to legislative mandates and has executed the requirements better than expected, relative to other federal agencies, especially during the past two decades. This was true for NEPA environmental impact statement requirements (Andrews, 1976; Cortner, 1976; Wichelman, 1976); for public involvement and open planning (Mazmanian and Neinaber, 1979); for comprehensive river basin planning (Lord, 1984; Major and Schwartz, 1990); and for implementation of the Principles and Standards (WRC, 1973) and Principles and Guidelines (WRC, 1983) for water resources planning. Embedded in the important innovations in planning was the idea that planning was not simply an engineering design-driven implementation of the most cost-effective project to meet specified purposes, but rather was a process to develop options and evaluate them against multiple societal objectives, including economic, social, and environmental needs. The innovations were aided immensely by a robust, university-based, and federally funded water resources research program that strongly influenced the manner in which water resources investments were evaluated. The best known outcome of such a joint effort between the universities and the federal water resources agencies was the influential Harvard Water Program that culminated in a classic "bible" for water resources planning, the "Design of Water Resource Systems" (Maas et al., 1962). This treatise, along with other comparable efforts stemming from the Harvard Water Program (Major, 1977), became the precursor to the "Principles and Standards" governing federal water resources planning.

A second wave of innovation among federal agencies was precipitated by President Carter's Water Policy Initiatives. These called for substantive changes in evaluation procedures; incorporation of water conservation into planning as a project alternative; upfront financing of federal water projects; concern for instream flow requirements for aquatic ecology; and a host of other reforms. Again these were slowly incorporated into agency procedures--that is, as fast as Congress got around to recasting them as provisions in law. Hence, the Corps initiated a major effort for developing water supply and conservation planning procedures and analytical tools for water demand forecasting (U.S. Army IWR, 1980) in order to complement the requirements of the Principles and Standards and President Carter's policy initiatives *despite the fact that the Corps did not have an authorized single purpose water supply mission*. In 1985 the Corps initiated a program to develop procedures for risk analysis for dam safety (Stakhiv and Moser, 1987) that led to an ongoing program of applying risk analysis techniques to all aspects of the planning, design, and operations and maintenance program, from navigation channels and dredged material division to freeboard on levees and the optional design of a flood warning and evacuation system. Currently the Corps is engaged on a national study on drought management planning that will develop drought preparedness procedures for large cities and rural communities, as well as for each of the Corps-operated reservoirs. The importance of these slow but permanent changes in water management philosophies is that these procedures also would serve concurrently to mitigate the uncertain effects of climate change (U.S. Army IWR, 1991a, b, c).

There is constant change and adaptation--to policies, to extraordinary events, to changes in public values. While there are few policies designed to explicitly deal with climate change, and certainly no comprehensive strategy exists, the countless practices and procedures embedded in an agency's "business practices" designed to deal with climate variability and changing water demands more than adequately serve as a practical surrogate. For it should be recognized that the business of the Corps, as an example of a federal water management agency, is to deal with the prevention and mitigation of natural climate-induced hazards. The Corps inherently deals with climate variability, so that the intricately interwoven and largely cumbersome procedures that have evolved over time should also serve CO_2-induced climate change. In fact, growth in population, shifting regional water demands, and changes in sectoral water uses *all pose a greater and growing perceptual challenge to water management than does climate variability and hydrologic uncertainty*. Global population is expected to double before CO_2 doubles. Today water management policies and planning procedures are formulated to be more responsive to water demands, public preferences, regulatory and legal constraints, and institutional responsibilities than they are to supply uncertainty. The potential impacts of climate change merely represent *one more exogenous factor to consider* in a multipurpose and multiobjective tradeoff analysis.

Principles and Practices That Complement Climate Change Adaptation

There is a continual process of conceptual, technical, and technological adaptation. It is slow, cumbersome, meandering, seemingly inefficient--but it is persistent. There is a considerable lag between the concepts as they appear in the literature and their implementation by the federal agencies. Yet, there should be a period for testing of ideas. Very few notions that appear in academic literature have immediate and practical applications. There are competing and conflicting ideas. Agencies with public responsibilities must also take the time to develop, test, peer-review, refine, and, most importantly, develop procedures that are consistent with numerous other rules and regulations and are understandable to the average scientist, engineer, biologist, and economist who must use these principles and procedures in their everyday work.

One cannot separate or isolate a single facet of an agency's overall ensemble of tools, techniques, and dominant problem-solving culture and simply focus on how that agency deals exclusively with, say, wetlands, endangered species, or climate change, for that matter. Decision making has become much more than the technically dominated endeavor that it was in the 1950s and 1960s. A vast array of changes in water resources management in the past 25 years, since the passage of the Water Resources Planning Act of 1965, has made it virtually impossible to pinpoint a dominant factor of change. The promotion of public involvement in planning has as much influence on project decision making as does benefit-cost analysis or the introduction of risk analysis or project cost-sharing.

As such, there is continued adjustment and adaptation now from many technical fields--not just engineering or hydrology. Changes in societal preferences now are transferred and transformed through environmental regulations, selection of ecological valuation models, the NEPA process, public hearings, reviews of planning documents, selection of alternatives, cost-sharing, financing, etc. Planning, design, and operation are now an open democratic amalgamation of numerous contentions, voices, and values that collectively serve to slowly change the course of an agency's dominant technical paradigm and in time take over steering the agency itself.

So, whether the issue is the proper accounting for the economic value of water, the role of wetlands in maintaining water quality, or the consideration of the role of contemporary water conservation practices in the overall approach to water resources management, all these responses have a bearing on how we address climate change--for they are complementary and mutually reinforcing responses to a phenomenon that will simultaneously affect countless interacting social, economic, and environmental processes. Hence, the recent works of Gibbons (1986), Frederick (1986), and Wahl (1989) concerning the economic valuation of scarce water resources are just as important as the debate centering on which hydrologic methods should be used to better understand the potential impacts of climate change (Chahine, 1992).

A large public agency like the Corps responds as any institution would and should--it proceeds deliberately and selectively, for the *implementation* of public policy requires much more certainty, uniformity, and reliability than is offered through the realm of academic literature. It is the thesis of this paper, therefore, that there are many divergent paths that, *de facto*, serve to provide the practical foundation for the principles espoused regarding adaptation to climate change.

Integrating Adaptive Strategies into Conventional Practices

Reservoir reallocation has been one of the traditional ways of adapting to changing water demands and uses. The Corps has engaged in countless studies, many driven by the growing demand for municipal and industrial water supply by urban areas. The Corps owns and operates approximately 600 reservoirs, including locks and dams, wherein approximately 215 million acre-feet (265.2 billion cubic meters) of single and multipurpose water is stored. Of this total, there is approximately 109 million acre-feet (134.4 billion cubic meters) serving multiple purposes, with approximately 74 million acre-feet (91.3 billion cubic meters) having municipal and industrial water supply as one of those purposes (U.S. Army IWR, 1988).

Corps of Engineers field offices have studied possible reservoir reallocation of existing storage for municipal and industrial purposes for many years--both formally as a result of congressional authorizations or as part of other related comprehensive studies, where reallocation was one among many possible alternatives to more efficient water resources management.

The studies illustrate many different ways in which reallocation h[illegible]n considered (U.S. Army Institute for Water Resources, 1988), foremost among which are:

(1) Use of water supply storage not under contract
(2) Temporary use of storage allocated for future conservation
(3) Storage made available by change in conservation demand or purpose
(4) Seasonal use of flood control storage during dry season
(5) Reallocation of flood control space
(6) Modification of reservoir water control plan and method of regulation
(7) Raising existing dam (to increase storage)
(8) System regulation of Corps and non-Corps reservoirs

But this is just the technical, physically based prerequisite for <u>choosing</u> an appropriate option. The adaptation to changes in demands and water uses coincides with changes in the manner in which we evaluate the relative worth or value of these changes. With every reallocation study there is a corresponding analysis of operating changes and impacts on instream flows and downstream biota; on the economic value of water; on water conservation efforts; on recreation values and other associated purposes, etc. Each study takes on a comprehensive view of resource management requiring public involvement, EISs, public review, and debate. More importantly, perhaps, is that when one reexamines old problems, new evaluation rules come into play--the discount rate, cost-sharing, upfront financing, water conservation, emergency drought procedures, dam safety/flood evacuation procedures, risk analysis, new hydrologic models, better data, etc.

Hence, the range of studies includes large-scale comprehensive studies authorized for lake level regulation schemes for the Great Lakes (IJC, 1990) as well as recent studies that ask for examination of the operating schemes of river basins such as the Missouri River, Columbia River, Rio Grande, Savannah River, Apalachicola-Chattahoochee-Flint Basin Study (Atlanta water supply) down to the smallest scale that deals with specific reservoirs for reallocating small amounts of storage for municipalities. The restoration of regulated rivers to a semblance of their natural states has also preoccupied planners recently. The planned restoration of the Kissimmee River and the flow into the Everglades in Florida is a major effort for the Corps. Few have explicitly dealt with climate change, and none have factored climate change into the final evaluation of alternatives. Yet all the studies, through their use of more sophisticated models, extended data bases, and more refined economic techniques have contributed to a better understanding of the systems and introduction of management measures that result in more robust and resilient operation. This does not necessarily mean more reliable or risk-free operation, only that there are more degrees of freedom to adapt to unforeseen circumstances by the introduction of various compensatory measures. We have moved from "fail-safe" to "safe-to-fail." In other words, residual risks are made explicit to public decision makers, evaluated in economic terms, incorporated into risk-cost tradeoffs, and used as the basis for designing complementary measures that reduce or eliminate those risks. For example, rather than building an expensive flood protection project (reservoir or levee) that provides a level of protection against a flood with 200-year recurrence, the Corps would now design a project whose size/scale is determined largely by the maximization of net benefits decision rule. This may turn out to be a 70-year level of protection, *complemented by* a flood warning and evacuation system (Stakhiv and Hanchey, 1989).

Two relatively recent research initiatives were undertaken that serve as a methodological complement to the analysis needed for the explicit consideration of risk and uncertainty and choosing the most reliable balance between "hard" flood control measures and complementary "soft" measures. An integrated flood damage sensitivity analysis procedure was developed to explicitly examine and quantify the influence that uncertainty in various components of the flood damage computation procedures has on the final benefit-cost analysis of alternative flood damage prevention measures, and whether and how the uncertainty affects the optimal design of the alternative measure and the choice of alternative (Ratick and Du, 1989). Soon thereafter, the principles and methods were converted into required procedures as planning guidance for Corps of Engineers practitioners in the form of an Engineer Circular (U.S. Army, 1992). This circular requires that all analyses conducted for new projects conform to the new analytical framework based on a Monte Carlo simulation of all the significant decision variables and parameters that comprise a typical flood damage reduction study. This method alone is a great step forward towards the kinds of analyses that are needed to deal with decisions that inherently center on climate variability and uncertainty.

A comparable risk-based research effort was conducted to better quantify the reliability of flood warning and evaluation systems (Haimes et al., 1992). The performance characteristics of various systems configurations can now be quantified in terms of warning time, false alarms, and flood damages prevented for various selected threshold levels of evacuation lead time and flood stage. A multiobjective decision tree was structured to assist decision makers with selecting the optimal course of action at each time increment and phase of alert and evacuation. The key point of this work is that flood warning and evacuation systems, which were previously *assumed* to be reliable and were routinely substituted for flood control structures with known reliability, can now be compared on the same analytical basis, providing a true complementary flood damage reduction *system*.

Other examples of adaptation to changes in demand that also serve the purposes of climate changes include a range of current authorities to analyze new allocation and operation schemes. For example, Section 216 of the Flood Control Act of 1970 is a standing authority that enables the Corps, with the approval of Congress, to review the operation of an existing project and recommend project modifications "when found advisable due to significantly changed physical or economic conditions ... and for improving the quality of the environment in the overall public interest." These studies are conducted in the same manner as are conventional feasibility studies authorized by Congress, and all the planning and evaluation procedures apply. Since the 1986 Water Resources Development Act (P.L. 99-662 and the subsequent acts of 1988, 1990, and 1992), numerous specific projects have been authorized for restudy along with larger scale studies of the Great Lakes (Section 706, WRDA 1986); the Upper Mississippi River Plan (Section 1103, WRDA 1986); and the Kissimmee River, Florida (Section 116, WRDA 1990).

The two recent notable examples of a system-wide operation review study have been conducted by the Corps for the Columbia River and Missouri River (U.S. Army Hydrologic Engineering Center, 1991a, b). Both studies were prompted by an accumulation of changing water uses and increasing demands on the system that were not foreseen during the design of the systems, accentuated by increasing conflicts among uses exacerbated by recent experiences in climate extremes--floods and droughts. In the Columbia basin, increased irrigation demands compete with hydropower and the need to enhance the dwindling anadromous fishery. In the case of the Missouri basin, the recent three-year drought caused a review of the existing Master Water Control Manual in light of the large increase in recreation, the importance of Missouri River augmentation of flows to the Mississippi for commercial navigation, and the explicit inclusion of water regulation criteria for endangered and threatened species.

In both of these systems analysis operating studies, new social, economic, and hydrologic data were introduced along with new analytical tools, foremost among which was a mathematical programming optimization model, called a network-flow model. A considerable amount of study was undertaken to quantify both the supply and sectoral demands on each of the systems and to develop economic benefit functions for each of the authorized purposes as well as for implicit or incidental water management purposes (e.g., white water rafting, instream flow needs for aquatic ecosystem maintenance, etc.). Upgrading the hydrologic analysis and conducting numerous sensitivity tests have led to a refinement in the understanding of the groups of reservoirs as a system and of the operating flexibility of that system under a broader range of climate variability and unforeseen demands.

In fact, the aggregation of analytical steps, such as risk analyses, economic optimization sensitivity analyses, risk-cost tradeoffs, factoring in environmental constraints, and testing of countless permutations of single reservoir and multiple reservoir allocation and operating schemes under a variety of historically likely combinations of droughts and flood is essentially the type of analysis that should lead to improved robustness and resiliency of water management systems. These comprehensive systems approaches are just the practical expressions of what a generation of theoretical water systems analysts have advocated for sensible management, *both for contemporary needs and for conditions of future uncertainty*. Fiering (1976) discusses the brittleness of optimal solutions, i.e., the failure of optimal (efficient) solutions to tolerate ambiguity, changes in technology, deviation from design assumptions, and the use of highly complex mathematical algorithms based on nonrepresentative statistical distributions to fit empirical data. Fiering essentially advocates the examination of alternative solutions that may be less efficient but that are more robust in accommodating the inevitable uncertainty associated with planned outputs (i.e., strategic uncertainty). He asserts that, indeed, "conventional wisdom (i.e., engineering judgment) might be selecting non-optimal but significantly more robust results than our finely-tuned but brittle mathematical models."

Hashimoto et al. (1982a, 1982b) expand on Fiering's original terminology introduced to account for risk and uncertainty inherent in water resources system performance evaluation. It is clear that the five terms listed below simply represent a set of descriptors that characterize and extend the key components of more traditional engineering reliability analysis i.e., they focus on the sensitivity of parameters and decision variables to considerations of uncertainty, including some aspects of strategic uncertainty. These terms are:

Robustness--describes the overall economic performance of a water resource project under uncertainty of future demand forecasts, complementing traditional benefit-cost analysis. This extends Fiering's definition from one of sensitivity of system design parameters to variability in future events to one of the sensitivity of total costs to variability in forecasts.

Reliability--a measure of how often a system is likely to fail.

Resiliency--how quickly a system recovers from failure (floods, droughts).

Vulnerability--how severe the consequences of failure may be.

Brittleness--the capacity of "optimal" solutions to accommodate unforeseen circumstances related to an uncertain future.

Fiering continued his examination of the physical, theoretical, and empirical bases of optimal reservoir system design (Fiering, 1982). He uncovered the not too surprising result (to engineers) that decisions based on many judgmental and empirically based engineering design practices related to the reliability, resiliency, and economic behavior of alternative water resources solutions were not that much different than the "theoretically" determined optimum. The point of risk analysis in a project planning and design setting, however, is not necessarily to confirm the validity of current engineering design practices or use of standards, although this may be the ultimate outcome of the analysis, but to use the information about uncertainty and risks in order to create a firmer basis upon which to formulate and choose among alternative solutions.

Emphasis on Demand and Variability

During the past 15 years, there has been a noticeable shift from supply-side planning by federal water agencies to demand management and more effective operation of existing systems. The reason for this emphasis is that water resources management has essentially responded to changes in demands and shifts in public values regarding the relative value of project purposes. At a national scale, it is clear that a combination of countless small regulatory, legal, economic, and technological actions have clearly resulted in a major shift in water use trends that, as late as 1975, were forecasted to be three and four times higher than actual water use. Credible contemporary estimates of water use for 1980, 1985, and 1990 (Solley, Pierce, and Perlman, 1993) are superimposed onto Figure 1, which shows the range of water use forecasts developed by a large number of respected and influential commissions in the United States. Water quality regulations accounted for the largest proportion of the reduction in water use, forcing greater industrial recycling. This was accomplished despite a doubling of manufacturing activity between 1970 and 1980 (Foxworthy and Moody, 1985).

While dramatic improvements in analytical techniques have been introduced to vastly improve our understanding of the effects that uncertainty in contemporary climate and hydrologic variability has on our range of choices for water management, the real revolution has been in the acceptance of a wide range of non-structural, institutional, market-based policy instruments as a way of controlling demand. As mentioned previously, these water demand management measures have been advocated for a long time, at least since the influential U.S. National Water Commission (1973) report. Implementation of these innovative measures has been slow but steady; in the lexicon of ecologists it is known as "punctuated gradualism." The important factor is that extremes in contemporary climate variability (severe droughts, floods, or hurricanes) catalyze or punctuate a societal response to deal with the problems of extremes in natural hazards and the accumulation of inefficient uses and practices regarding resource utilization. This is perhaps the most direct and effective, albeit inefficient, mechanism that society has to adapt to the combination of changing climatic signals and increasing societal demands on resources.

The California drought of 1987-1992 is but the most recent and best documented example of how the adaptive process works. It was not an efficient process and serves as yet another classic example of Lindblom's (1959) description of public policy formulation as "disjointed incrementalism." Yet it seems to be the only realistic way that complex democratic societies can function. California had a prior drought experience in 1976-1977 that caused many reforms in operating and regulating the extensive water management system, along with a few significant institutional and water demand management measures that were undertaken, although many more were proposed in the aftermath of that drought. This is evidenced by the fact that in the interim decade (1980-1990) population had grown significantly (+27%) and is projected to grow another 40% by 2010 (U.S. Army IWR, 1993). Yet, the interesting piece of information is that while urban water use grew from 14% (in 1980) to 16% (in 1985) of total water use in California, irrigation declined from 84% in 1980 to 81% in 1985 so that total water use dropped by 2% in that five-year period and is not expected to reach 1980 levels again until the year 2010. During the drought itself, especially in 1991 and 1992, agricultural water use declined by about 20-30%.

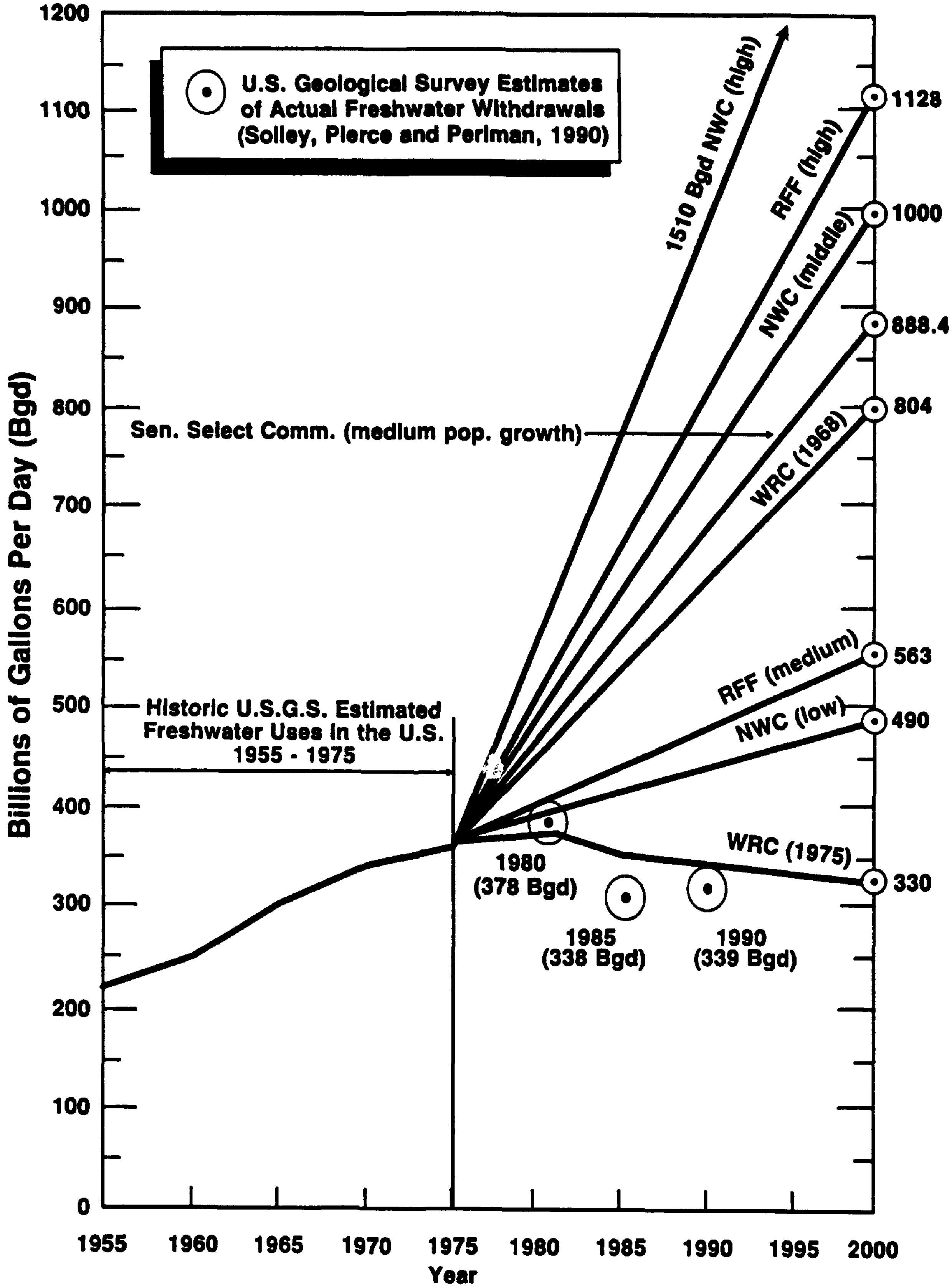

Figure 1. Historic and projected fresh water withdrawals, 1955-2000.

Source: U.S. Congress, 1980. State and National Water Use Trends to the Year 2000. Congressional Research Service, No. 96-12.

The point is that the 1976-1977 drought engendered considerable reforms in management of supply, but more importantly a considerable reduction in water demand. The recent and much more intense drought spurred consideration and implementation of an even bolder set of water management activities. These included a broad range of strategic (long-term), tactical (short-term), and contingency (emergency) measures that were available but were never implemented for a variety of legal, institutional, or technical concerns. Long-standing legislative constraints on the operational flexibility of California's Central Valley Project were removed by Congress, which also reallocated 800,000 acre-feet of water instream uses to protect aquatic habitat. The California State Water Control Board published a Water Rights Decision requiring stricter adherence to water quality standards during droughts, again to protect the aquatic ecology, especially in the Sacramento-San Jaoquin Delta. Price rationing and water use rationing were used in conjunction for urban areas, resulting in a successful program of urban water conservation during the drought and one that will have lasting effects in the future.

The drought forced water agencies and water professionals to seek creative solutions to water shortage problems, showing that market forces can be effectively used to reallocate restricted water supplies. In 1991, California established the Drought Emergency Water Bank at the height of an accumulation of six years of deficit. There was more water offered for sale than there were willing buyers, even at a reasonable price of $125 per acre-foot ($125/1,233m^3). For comparison, the cost of developing new water supply sources today ranges from $300 to $1,000 per acre-foot. All in all, many more administrative, institutional, and legislative changes were instituted at all levels of government. These will serve as the basis for a new water management ethic until the next major perturbation stresses the system. The measures that were implemented by California are the very same set of measures that are offered for adaptation to climate change. The reality is, as the California experience has demonstrated, that society is continuously adapting to the combined forces of climate variability and shifting demands.

Improving the Value of Climate Change Impact Analysis

Climate change impact analysis has limited and perhaps dubious value for the water resources manager *at the present time*. This is primarily due to the contradictory outputs of the GCMs and lack of specific and credible regional and watershed-level projections. Water managers recognize that society is capable of adapting to climate perturbations, stresses, and variability, and it seems likely that climate change could be considered as an extension of current variability. This brings up the question of the value of climate change impact analysis to water managers. There seems to be agreement among the water management community that the current crop of climate impact assessments are not particularly useful for any level of contemporary water management decisions, nor are they likely to be for at least the next decade, if not beyond. What, then, should the role of these analyses be in decision making and how can they be improved to be more useful to the water manager?

The major point made herein is that because of the high degree of overlap between actions and measures typically undertaken by water managers to deal with contemporary climate variability and anticipated climate change, the water management community does not need to undertake any radically different strategies to deal with the climate change phenomenon. But there are many more unmanaged watersheds dependent on unregulated streamflow and groundwater. What response strategies should be considered in those situations? The most severe impacts would appear to be in the environmental sphere--forested ecosystems, wetlands, lakes, ponds, aquatic habitat, and associated species. Water quality analysis, under the combined conditions of temperature increase, lower runoff, and various scenarios of projected pollution loadings, needs to be conducted to better understand the range of responses available to water managers in the future and the consequences for instream aquatic biota.

If variability changes considerably under any of the global warming scenarios, we may have to contend with longer, more intense droughts together with larger and more frequent flood episodes. What are the water management implications of those possibilities for dam safety, flood warning and evacuation, or even for the flood insurance program? But most importantly, how is the contemporary decision maker to decide what is important when neither a uniform evaluation framework nor the appropriate tools have been developed for a rational examination of the issues and options. The relatively imprecise and often contradictory information available to the managers today is simply not helpful in the practical decision-making settings that they typically confront.

That is why in the most recent update of the IPCC impact assessment report (Stakhiv, Lins, and Shiklomanov, 1992) the principal recommendations of the IPCC were that:

- increased variability of floods and droughts will require a reexamination of emergency design assumptions, operating rules, system optimization, and contingency planning for existing and planned water management systems;
- more studies on hydrologic sensitivity and water resources management vulnerability need to be focused on arid and semiarid regions and small island states;
- a uniform approach to climate change and hydrologic sensitivity analysis needs to be developed for comparability results.

The last point, stressing the need for developing uniform, comparable evaluation approaches, is essential for usefulness and credibility. There is no compatibility whatsoever among the hundred or so water resources related climate change impact studies, either on the choice of GCMs, hydrologic evaluation methodology, IPCC scenario assumptions, or interpretation of results (Stakhiv, Lins, Shiklomanov, 1992). The first steps in developing such a methodology were taken by the IPCC (1992), but the current generation of studies in progress were initiated well before the IPCC guidelines were published.

A contemporary initiative is the development of mesoscale GCM models that correspond to interbasin scale impact analysis, with a much finer scale of resolution. While the analysis of site-specific and project-specific climate change impacts is still in the distant future, a great deal of progress and many insights can be made as to watershed level responses in the hydrologic regime, groundwater regime, and associated ecosystems. Better formulation and estimation of water management vulnerability estimates are needed to take into account future shifts in water demand that respond to the range of economic, technological, and institutional adaptations.

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A FRAMEWORK FOR ANALYZING WATER RESOURCES MANAGEMENT UNDER CLIMATE UNCERTAINTY

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ABSTRACT

The focus of this work is the identification and assessment of analytical modeling elements that are existing or needed for examining a range of climate scenarios, their related impact on municipal and industrial water demand, and water resources management alternatives to accommodate those impacts. The study is restricted to the Potomac River basin, which includes parts of Pennsylvania, Maryland, Virginia, West Virginia, and all of the District of Columbia.

The principal water resources of the basin are surface sources consisting of the river itself, which is augmented by three regulating reservoirs, and several direct-supply reservoirs used by the suburban water utilities in the Washington metropolitan area. The basin's major water demands are an electricity generating station using once-through cooling and the municipal demand of the Washington metropolitan region. These water resources and demands are expected to be affected simultaneously by potential changes in climate. The modeling sequence investigated as a framework for analysis includes regional climate models, water availability/supply models, water demand/use/socioeconomic forecasting models, water operations models, and evaluation/decision-making models. The use of this modeling sequence will allow analyses of linked impacts on supply and demand, and their management.

INTRODUCTION

The water resources of the Potomac River basin offer a good opportunity to explore a framework for analyzing water resources management under climate uncertainty. The largest use of the managed resources is municipal water demand. There are, however, a number of other water uses that exist or benefit from management of the water resources. These include water quality, fisheries, electricity generation, navigation, and canoeing and kayaking. In addition, the issues of flood control, consumptive use, and erosion and sedimentation will likely be impacted by climate uncertainty.

The principal water resources of the basin are the river itself, which is augmented by three regulating reservoirs, and several direct-supply reservoirs used by the suburban water utilities in the Washington, D.C., metropolitan area (WMA). The management of these resources for municipal water supply is divided among the individual water utilities and the Interstate Commission on the Potomac River Basin. In the rural areas of the basin, community water systems are managed by individual towns or small regional service authorities. Their resources are small facilities including river intakes, surface reservoirs, and wells.

The term climate uncertainty recognizes that future climate conditions may not be the same as those at present. In this case climate is taken to be defined as "the average ... condition of the weather ... over a period of many years as established in absolute extremes, means, and frequencies of given departures from these means, of temperature, wind velocity, precipitation, and other weather elements" (Merriam, 1976). This definition of climate is conditioned on being referenced to a particular place or region on earth.

Planning for the future management of water resources requires an assumption about climate. Until recently, climate impacts on water resources planning and management have been assumed to be stationary. However, the findings from recent examinations of trends in weather have led to investigations of possible future changes in climate. The indications are such that future climate can no longer be assumed to be stationary in its impact on water resources management.

Water demands and resources are expected to be affected simultaneously by potential changes in climate. This study describes a framework for analyzing the effects of changed climate on both demands for water and the available resources to meet those affected demands.

CURRENT WATER RESOURCES MANAGEMENT ISSUES

In a moderately sized (15,000-square-mile) East Coast river basin it is not surprising that water resources may be managed simultaneously for a number of purposes. In the Potomac River basin, these purposes include municipal and industrial supply, water quality, flood control, maintenance of fisheries, consumptive use, white-water recreation, estuarine issues, navigation, hydropower production, storm-water runoff, and the reduction of erosion and sedimentation. The important management considerations for municipal water supply and consumptive use are presented below.

Water Supply (Municipal)

The Potomac River basin provides drinking water to more than 4 million inhabitants. Most of this water is provided by surface-water sources. Demands are rising fairly rapidly, especially within the WMA, increasing the likely magnitude of drought consequences. The potential for a decrease of flows due to climate change would only exacerbate the situation.

Because of the mutual dependence on the Potomac River for obtaining raw water supplies and the close proximity of the water supply intakes for the three major water utilities, an unusual degree of cooperation exists between these utilities. As early as the drought of 1966, the need to consider additional water resources became apparent. By the late 1970s major efforts had been undertaken to develop coordinated operating procedures that increased efficiency for the WMA water supply system. Between 1979 and 1982 this cooperative operation was formally institutionalized by several major agreements.

The Water Supply Coordination Agreement binds the utilities to joint operations during low flows. This agreement designates the responsibility for scheduling water supply releases from the Jennings Randolph and Little Seneca regulating reservoirs, and allocating water supply withdrawals, to the Section for Cooperative Water Supply Operations (CO-OP Section) of the Interstate Commission on the Potomac River Basin. In order to carry out its duties, the CO-OP Section has developed procedures for scheduling releases and withdrawals consistent with each utility's operating policy, while balancing the resources.

Water supply planning is less developed in the numerous small communities outside the WMA. Although their water supply needs are much smaller than in the WMA, various problems exist. These water supply problems can be separated into four major categories: source quality, source quantity, treatment capacity, and distribution capacity. Climate variability affecting dependability of supplies and seasonal demand patterns would undoubtedly increase the vulnerability of the many systems.

Consumptive Use

The Maryland Department of Natural Resources (DNR) has determined that the Potomac River's water is fully appropriated during periods of low streamflow. In order to protect the water rights of prior appropriations to surface diversions and upstream reservoir releases, the Maryland DNR has developed consumptive-use regulations pertaining to Potomac River diversions upstream from Little Falls. The regulation requires new consumptive users to provide low-flow augmentation storage.

The Maryland DNR defines consumptive water use as "that portion of a water withdrawal which, as a result of evaporation, interbasin diversions or other means, is not returned to the source to be available for subsequent use." The Maryland DNR, acting on the advice of the Interstate Commission on the Potomac River Basin/CO-OP Section, will determine when flow conditions justify implementation of the consumptive-use restrictions.

The Potomac Electric Power Company (Pepco) has proposed increasing its electrical generating capacity at Dickerson, Maryland. Pepco and several other users would be the first entities to be required under the Maryland water use regulations to provide surface-water storage for low-flow augmentation. The U.S. Army Corps of Engineers is currently reevaluating the allocation of storage space in Jennings Randolph Reservoir in order to determine the technical feasibility of reallocating space from flood control storage to water supply (U.S. Army, 1989). However, climate change could affect the need for more flood control storage as well as low-flow augmentation.

ASSESSMENT OF ANALYTICAL MODELING FOR WATER RESOURCES

The management of water resources in the Potomac River basin is accomplished by various techniques and procedures. Many of these are computerized for speed, consistency, and accuracy of implementation. To date there has been no consideration of the possible effects of climate change in water management for the Potomac. However, this section begins with a discussion of potentially applicable models of climate change. That discussion precedes descriptions of numerical models and other techniques available, or in use, in the following sequence of water management: availability/supply, demand/use/socioeconomic forecasting, operations, and evaluation/decision-making. In each phase of modeling, modifications could feasibly be made to models or techniques in order to assess the possible effects of climate change on water resources management.

Climate-Change Models

Global climate has been in a constant state of change for as long as records or other evidence are available. Beginning in the 18th century, however, man acquired the ability to affect climate through the greenhouse effect. This term actually refers to a phenomenon that has always been present: the surface temperature of the earth (and/or any other planet with similar atmosphere) is higher than would be the case if there were no atmosphere. The sun delivers an essentially constant short-wave energy flux of 345 Wm-2 to the top of the atmosphere. About one-third of this is backscattered into space, about one-half is absorbed at the earth's surface (160 Wm-2 on average), and the rest heats the clouds and the atmosphere.

A series of large, computationally intensive global climate models have predicted that rising concentrations of greenhouse gases in the upper atmosphere will produce, in the relatively near future, significant warming of most parts of the earth. Mean temperature increases are expected to be accompanied by changes in the level and in spatial and temporal patterns of precipitation. Taken together, these changes, if they occur, will change both the supply of and demand for water in urban areas, with potentially large impacts on water supply planning.

The best known global climate models are all general circulation models: they are dynamic models that simulate the physical processes of the atmosphere and the oceans as they are relevant to climate. The model coefficients are estimated from data for historical periods, when atmospheric, ocean, and climate data are either known or can be estimated. These models have been under development for the past two decades, and include the following:

- COM: National Center for Atmospheric Research community climate model
- GISS: NASA Goddard Institute for Space Studies
- GFDL: Princeton University Geophysical Fluid Dynamics Laboratory
- OSU: Oregon State University

Many similarities exist among models; e.g., all are based on integration over the globe of a set of dynamic equations (Stockton et al., 1989).

Equation	Variable
Hydrostatic	Temperature
State for atmospheric gases	Mixing ratio
Continuity of mass	Vector horizontal velocity
Conservation of momentum	Vertical momentum
Conservation of heat	Geopotential
Conservation of moisture	Density

Some models, such as GISS, use a finite difference grid with node spacing on the order of several hundred kilometers, and several vertical layers. The six governing equations are written for each node. Others (GFDL and NCAR) are spectral models, with a wave number of 20 or 30 around the globe.

One area where the individual models differ significantly is in the selection of boundary conditions specified before solving the equations. Boundary conditions include assumptions regarding solar flux and vertical velocity at the top of the atmosphere, temperature or heat flux at the earth's surface, and sea surface temperature. Smaller scale processes are often parameterized, rather than included in the governing equations of the models. These include frictional forces on the earth's surface, condensation, and formation of clouds.

The results of all four models appear to predict warming of the lower troposphere, increased precipitation, and cooling of the stratosphere with high confidence. Warming of the upper troposphere is also predicted, but with only moderate confidence. Based on a projected effective doubling of atmospheric carbon dioxide during the next century, the models predict a rate of increase in global mean temperature in the range of 0.2 to 0.5 degrees Celsius per decade (IPCC, 1990). Anything in this range would be a more rapid rate of increase than any experienced in the last 10,000 years.

GCMs produce estimates of climate change, but because those estimates rely on as-yet unproven assumptions they are not particularly helpful in public policy development and analysis. Scenario approaches, based on a variety of physical or statistical arguments, are more appropriate for this purpose. These methods permit the identification and analysis of a variety of responses to a number of different climate-change scenarios. Recent EPA reports have reviewed a number of different scenarios of this kind (U.S. EPA, 1988, 1989).

These include transplant scenarios, which estimate how climate might change from time to time given a steady increase in greenhouse gases. Equilibrium scenarios depict the steady-state endpoint of a specified increase in greenhouse gases. Other scenarios use historical analogue or alternative sea-level-rise assumptions.

Water Availability/Supply Models

There have been a variety of water availability/supply modeling techniques applied to the Potomac River basin. They included risk and position analysis to evaluate the adequacy of existing reservoir storage, conceptual hydrologic modeling, and statistical modeling.

Two techniques have been developed (Hirsch, 1978) for evaluating risks in the operation of a water supply reservoir in the Potomac River basin (the Occoquan Reservoir in Fairfax County, Virginia).

Both rely on reconstructed historical streamflow data to derive estimates of the probabilities of certain specific events in the future with regard to water supply availability.

The first technique simulates reservoir contents under a set of assumptions about withdrawal rates and demand-reduction procedures. This technique uses the general risk analysis model (GRAM). The results of the GRAM simulation for the Occoquan Reservoir are in the form of estimates of the probabilities that in any year certain demand-reduction procedures will have to be implemented.

Position analysis is used as the second analytical technique to evaluate reservoir water availability. In this procedure, probability distributions of future storage are estimated given existing storage and future withdrawal from the reservoir.

Conceptual hydrologic modeling techniques that simulate the physical processes of the hydrologic cycle also have been applied in the Potomac River basin. This method uses the Sacramento Soil Moisture Accounting model and the Extended Streamflow Prediction components of the National Weather Service River Forecast System. This method is described in Smith et al. (1982). The Sacramento model provides a conceptual accounting of the precipitation inputs to a drainage basin in a continuous manner. This model simulates the runoff process, the storage and movement of water beneath the surface, the transfer of groundwater to stream channels, and the evapotranspiration of water from soil and stream channels. It is calibrated for 26 sub-basins in the Potomac River basin. The Extended Streamflow Predictor is used to incorporate current estimates of soil moisture conditions and historical precipitation to develop forecasts of water availability based on current conditions and historical factors. This model is advantageous because of its physically based nature and its ability to predict high flows as well as low flows. However, because of the large number of sub-basins and the nature of physically based models, it requires much computation time.

Statistical modeling techniques were developed for streamflow forecasting to reduce computation time. A nonparametric regression technique was developed to produce distributional forecasts of the likelihood of flows falling below a critical level where water supply augmentation would be required. This method is described in Smith et al. (1987). This model uses the current estimate of base flow and historical streamflow data to forecast future base flows in a probabilistic sense. This forecast procedure is computationally simple and requires only daily discharge data for implementation. Its results, however, depend on the weighted average of historical observations and the forecast is sensitive to the weighting parameters used.

Water Demand/Use/Socioeconomic Models

The Corps of Engineers developed a model (U.S. Army, 1983) in which water-demand forecasts were based on population, employment, and household data. The output from this model was average monthly water service area demand from 1980 to 2030.

The population projections were developed by the Corps based on the 1976 Metropolitan Washington Council of Governments population forecasts (MWCOG, 1976), which were extended to the year 2030 through the use of logarithmic regression. Employment and households were also based on the MWCOG forecasts and input from local planning agencies.

Eight water service areas were developed for the MWA. Water use was disaggregated into six user categories: single-family residential, multi-family residential, commercial/industrial, governmental/institutional, federal government, and unaccounted-for water use. For each of the first five categories, a unit water use was developed for all eight service areas. The year 1976 was used as the base year for investigating unit water use. The indoor and outdoor water use in each category were separated to determine the effect of alternative water conservation plans on total water use. Average winter use was assumed to represent the indoor use. From the average monthly water demands obtained by the demand model, 1- and 7-day demands were computed.

The Interstate Commission on the Potomac River Basin developed a model (Holmes and Steiner, 1990) that also used demographic and water use data and unit use factors to forecast annual average water demands from 1985 to 2010.

Estimates of population, households, and employment to the year 2010 were based on the Cooperative Forecasting Program's Round IV totals (MWCOG, 1988). The model used numbers of single-family households, multi-family households, and employees to forecast annual average water demand. Water consumption per single-family household, multi-family household, and employee were estimated for the major water supply utilities.

Water use was disaggregated into six sectors: single-family residential, multi-family residential, employment, long-term wholesale, unaccounted-for, and process water use. Unaccounted-for water use is a constant percentage of total water use. Process water use is defined as water used inside the water treatment plant (particularly backwash water used in filtration and sedimentation basins).

Water demand was separated into base level (mainly indoor and nonseasonal employment water use) and seasonal (mainly outdoor and seasonal employment water use) categories. Base-level water demand is assumed to equal the lowest monthly demand within a given time period and seasonal water demand is the difference between all other monthly demands and the lowest monthly demands. Water use was not disaggregated when assessing water conservation savings. Varying percentages of savings were allocated to base-level demand and seasonal demand.

Both the COE model and the ICPRB model rely on existing unit use factors. There are no explicit terms dealing with weather parameters that may be affected by climate change in either model.

Water Operations Models

In times of plentiful water resources, the three major WMA water utilities operate quite independently. Plentiful water resources are considered to be adequate storage in local direct-supply reservoirs and sufficient natural flow in the Potomac River to meet water supply and environmental flow-by requirements. During such times, each of the three utilities has some flexibility in the proportions by which they use the local reservoirs and river intakes to meet their needs. The factors that are considered in making these choices include relative head difference and energy cost of pumping alternative-source water to treatment and into distribution, relative quality of water and cost and difficulty of treatment, and capacity limits on treatment and conveyance.

However, when the flow in the river is (or is predicted to be) insufficient to meet that portion of unrestricted demands that relies on the river, water resources management is guided by a process that is based on a series of numerical models. It is conducted by the CO-OP Section of the Interstate Commission on the Potomac River Basin.

The overall objectives are to make the most efficient use of all water supply facilities, including the Potomac River, Jennings Randolph Lake, Occoquan Reservoir, Triadelphia Reservoir, Duckett Reservoir, and Little Seneca Lake to meet all water supply needs for the Washington metropolitan area.

Specifically, the models that guide the process are a set of long-range reservoir withdrawal programs and a program that schedules low-flow augmentation releases from upstream and downstream reservoirs.

The long-range reservoir withdrawal programs require current storage and date. They determine the maximum constant future direct-supply withdrawal amount that will just meet the refill objectives on the following June 1. The refill objectives are met by comparing the candidate withdrawal rates with inflow sequences for the period June 1, 1930, through May 31, 1982. If climate change causes a significant difference or trend in river flows, then the basis for computing refill probabilities would change. Consequently, the calculated withdrawals would also change. With altered input flow sequences and a modest amount of reprogramming, the programs could be used to test the results of climate-change scenarios.

The program that schedules low-flow releases from augmentation reservoirs is an accounting algorithm that compares daily demand with the results of the direct-supply reservoir withdrawal programs and the flow in the river. If the flow in the river will not meet anticipated demands for water, the required releases are determined from the augmentation reservoirs. If the low-flow regime or predictability of river flow is altered significantly by climate change, operational changes will be required. Changes in flow regime caused by climate change could be tested on the existing programs with a modest amount of reprogramming.

It was not determined if any areas in the Potomac River basin use the WMA use models for water supply management.

Evaluation/Decision-Making Models

There are two evaluation/decision-making models for the water resources system of the WMA. They operate on a weekly and daily time step, respectively; and in so doing, relate reservoir storage, riverflows, and water demands.

The Potomac River Interactive Simulation Model (PRISM) is able to describe changes in the conditions of the physical water supply system through time based upon results from decisions about the operation of that system. The model incorporates the provisions of the Potomac River Low Flow Allocation Agreement, and thus can be a useful predictor of conditions of extreme water shortage. Inputs to the model include weekly streamflow and water-demand data, water use restriction decision rules, and constraints on reservoir operation. Outputs include water available to each of the three major WMA water utilities, and resultant reservoir storages and river flows.

The other evaluation/decision-making model, Daily Operation Simulation Model (DOPSIM), is similar to PRISM except that it operates on a daily time step. DOPSIM was developed to refine daily water system operating rules. A daily operation simulation model was needed because of (1) the daily nature of utility operation, and because (2) updated information from the U.S. Geological Survey (USGS) indicated that travel times from upstream reservoirs (Jennings Randolph and Savage) were not 7 but 4 to 5 days (Trombley, 1982), (3) streamflow forecasts changed day to day, and (4) water use varied substantially day to day (Sheer, 1982). This model allows the same type of analysis of management strategies as the weekly simulation model PRISM except that it incorporates daily variations in demand and management strategies that better simulate actual operations. It is a basin-specific, multi-reservoir simulation model using historical streamflow sequences and forecasted daily water demands to simulate water supply system operations. It tracks reservoir releases and storages for system reservoirs along with water demands for each of the three main water supply utilities.

Both PRISM and DOPSIM require riverflow and water use information as input. This makes them well suited for analyzing the combined effects of climate change on resources and demands.

CONCLUSIONS

It is anticipated that, with some modifications, the water resources models for the Potomac River basin could be used to examine the key hydrologic processes and physical effects of climate uncertainty. It is also anticipated that the water management models could be used to investigate the potential influence of climate change on water demand. Investigative use of the models is expected to lead to future action plans and potential response strategies as we enter an era of uncertainty about climate and its effect on water resources and demands.

ACKNOWLEDGMENTS

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CLIMATE CHANGE AND WATER RESOURCES--SUMMARY REPORT FOR DEMAND-MANAGEMENT SESSION

Kyle Schilling, Chairperson
Peter Gleick, Ph.D., Rapporteur

The session on demand-management responses to climate change focused on several important issues, including the role of regulatory and voluntary approaches, water marketing, water transfers, and the economic advantages of demand-side solutions over most supply-side approaches.

In general, the group supported the premise of the Intergovernmental Panel on Climate Change regarding a conservative approach to climate change, which in this case means we should *today* undertake inexpensive options (such as demand management) rather than delay until complete information on climate impacts is available (if ever); that is, we should push to undertake cheaper measures sooner rather than later because of the risk of severe impacts, the low cost of some solutions, the long time required to provide definitive information on regional impacts of climate change, and the lag in the system (i.e., the inability to avoid at least some future impacts that are already in the works due to greenhouse gases already emitted).

Described below are the common themes of the discussion, some innovative solutions, barriers to solutions, and gaps in our understanding.

Common Themes: What Ought To Be Done Now?

Both supply-side *and* demand-side responses to climate change are necessary. As we have now come to realize, most (though not all) supply-side solutions will be expensive and ineffective. Alternatives for increasing supplies are very limited and expensive (recycling, desalination, cloud seeding, new facilities, and so on). Demand-side responses seem easier, cheaper, and faster to implement. More effort at evaluating and implementing demand-side solutions is necessary.

Among the approaches that should be considered as part of demand management are both regulatory and voluntary techniques. One of the most important approaches is the proper pricing of water. When water is not correctly priced (or priced at all), water markets cannot work, nor can proper incentives for conservation be put into place.

Frederick described two levels to demand management: (1) laws, practices, and allocations and (2) pricing policies. These include the following:

- The regulatory approach (e.g., preserving wild and scenic rivers, mandatory reductions, technology-based effluent standards).

- Voluntary approaches (e.g., prices to provide incentives, taxes, subsidies, water marketing).

Water marketing and flexible and voluntary water transfers also seem to be particularly powerful tools, though much more work is needed to solve problems with these methods. There is much opportunity for water markets, innovative pricing, and contingency planning. The California Water Bank, set up in response to the ongoing California drought, is an example of innovative marketing. Though many flaws in the development of the bank need to be worked out, it is a step in the right direction. However, if we wait for a crisis to appear before acting, the costs of responding after the fact are likely to be higher than the costs of taking demand-management actions now.

What Are Key Impediments?

There are many inappropriate economic signals blocking effective demand-management programs, including the fact that block rates for water use are declining; the full costs of water use are often not borne by users; externalities are not included (especially environmental externalities); water utilities are monopolistic, which hinders proper markets; and average-cost pricing hides the true costs of marginal water use. These are economic problems and can be mitigated by regulatory agencies or innovative utility actions.

Under current water laws, water conserved through demand-management actions is often lost to the user, which reallocates any water not put to effective use. This is a major impediment to conservation.

Groundwater is often poorly regulated, allocated, or understood. New approaches must be worked out to include groundwater problems. Approaches for dealing with groundwater may differ from approaches for dealing with surface water.

The difficulty of distinguishing quickly between natural variability or long-term climate change greatly complicates decision-making. Yet the appropriate policies may differ. How can be protect ourselves from making the wrong choice?

It was pointed out that this question of variability is one that must be faced, with or without climate change. If we have the flexible institutions or policies to reallocate supplies in response to these changes, we will be better situated to deal with climate changes as they occur.

Unfortunately, we tend to wait for an emergency or crisis to occur to implement these changes. We should have more flexibility built in from the start.

Some regions have no institutions to deal with these issues. Unless institutions can be developed or modified to work on issues of demand management, the implementation of suitable approaches will be seriously delayed.

What Are Innovative Solutions?

Various innovative solutions to some of the above problems were discussed, as summarized below.

To solve some of the serious environmental problems associated with water depletion, it is necessary to build environmental values directly into water practices. Water transfers/markets could include water for instream flow protection (e.g., the modified California Water Bank approach), or water rights could be assigned or sold to the environment if a mechanism for providing funding to the environment can be developed.

Institutions can permit and facilitate flexible water transfers and markets (e.g., the Bureau of Reclamation policy recently adopted to facilitate transfers, water banks, etc.).

Any water saved through efficiency improvements should be kept available to be leased, sold, or transferred, rather than lost or reallocated. Another alternative is to allow individuals or organizations to hold instream flow rights.

There is growing experience with active, successful demand-management programs at water utilities. This experience must be shared widely and encouraged. A superb example was given during the session by Stephen Estes-Smargiassi, who described the extensive demand-management activities of the Massachusetts Water Resources Authority.

What Research/Information Gaps Are There That Hinder Good Decision-Making?

These are described more fully in the above section on key impediments. These impediments hinder good decision-making.

On an operation level, questions need to be answered for specific river basins or hydrologic regions. For example, in the Colorado River system, how can we improve operating rules with prospect of long-term drought, and would these changes be any different under conditions of long-term climate change? How important is good advance information on future changes? Can good decisions be made without such perfect foresight?

Other questions need to be answered:

- How can environmental users pay their way when they have no economic resources?
- How can groundwater demand-management approaches be developed? How does one define boundaries and beneficiaries?
- How are water prices to be set?

The following people participated in the panel: Kyle Shilling (Chairman), Peter Gleick (Rapporteur), Stephen Estes-Smargiassi, Kenneth Frederick, and Richard Wahl.

COPING WITH CLIMATE CHANGE: BOSTON'S EXPERIENCE WITH DEMAND MANAGEMENT

Stephen A. Estes-Smargiassi
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Massachusetts Water Resources Authority

ABSTRACT

What can be done about climate change? What we know so far is that there certainly is more uncertainty about climate. There probably will be more demand; our evaluations of Boston's system indicate this. And, there may be less supply available, at least in the Northeast (Kirshen and Fennessey, 1991).

What I would like to offer today is one possibility of an adaptive response. Our experience at the Massachusetts Water Resources Authority indicates that successful demand management is possible. What we have developed is not a drought response or an emergency conservation program, but a long-term year-round demand-management program. A common response by water resources managers to demand management is that supply is sure, demand management is not. The evidence we have seen at this conference indicates that supply certainly seems to be less certain than was previously thought. I would like to present some of the mounting evidence that conservation does have some surety to it (Vickers, 1991).

A BRIEF HISTORY

A brief history of the MWRA system would help the readers evaluate whether our experience makes sense in their own circumstances. The MWRA is a wholesaler of water to 46 cities and towns in the Boston metropolitan area. We have about 477 billion gallons of storage and a safe yield from our major reservoir systems of about 300 million gallons per day, as well as about an additional 80 million gallons per day of smaller local surface-water and groundwater supplies owned and managed by cities and towns. Our system started serving about 180 families in 1652 (Floyd Associates, 1984). As Figure 1 shows, the system has grown over the years with new sources added, and other ones abandoned. Today, we serve about 2.5 million people in about 800,000 households. Over time, we developed new sources farther upland and farther outside of the core of the urban area in less populated areas as we contaminated or outgrew our closer-in resources. By the 1970s demand had again exceeded supply, and in the late 1970s we began to evaluate additional sources. After about 50 volumes of examination of existing supplies, projections of future demand, and analyses of alternatives, the basic conclusions of the report were that by the year 2020, we could be 50 percent over our safe yield or, as some said, we could develop new sources only to have them serve leaks and insufficient water practices, not people.

The MWRA Board of Directors decided that no decision was the best decision. They felt they did not have enough information to make a firm decision and asked the staff to try out demand management. The program we developed is essentially a reservoir-to-tap program. It looks at six principal areas of supply management: (1) leak detection, repair, and metering; (2) conservation and demand management; (3) improved use of existing sources; (4) water supply protection; (5) management and planning for the future; and (6) outreach and reporting.

The basic principles of the program were to carefully try out programs, to thoroughly evaluate whether they were successful or not, and then to decide whether we should go forward.

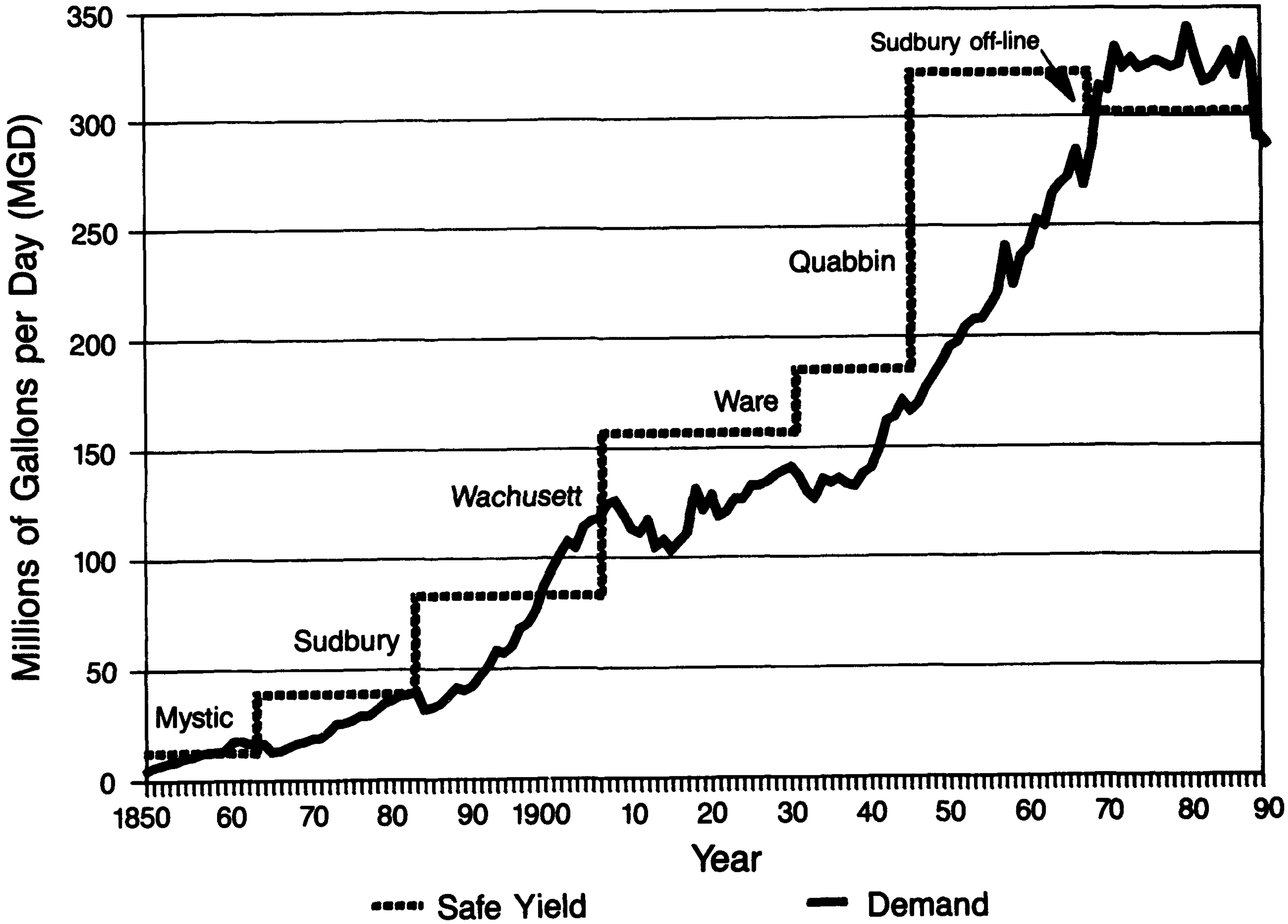

Figure 1. **MWRA water demand and supply 1850–1991.**

In this paper I will not dwell on the cost comparisons among alternatives except to say that demand management was certainly cheaper than almost all of the potential supply options we have available to us. Table 1 shows that comparison.

A basic principle of our program is one of equity among sectors. Perhaps you could express it as "joint suffering." As shown in Figure 2, in the 1980s about 38 percent of our water use was for residential users; 34 percent for industrial, institutional, and commercial users; and about 28 percent for system use and other unaccounted-water uses. We put together programs to deal with each of these three areas in multiple ways ranging from actions in our system (the wholesaler), to the local (retail) systems, to the individual users.

LEAK DETECTION, REPAIR, AND METERING

Leak detection and repair results in real water savings. It develops credibility for your overall demand-management program and has little negative fallout. It should be done early to reduce any sense that the system is not bearing its share of the burden. What the MWRA did in its program was to do a once-through survey of allpipes in our system and in the community systems, even though we do not own them. Once we did that, we required, through regulation, that all pipes be evaluated by the communities once every 2 years, that the repairs be made promptly, and that the community report back on the results. The results of the once-through were quite satisfying. We evaluated about 6,000 miles of pipes and found and repaired over 30 million gallons per day of leaks. Our experience demonstrates that between 7 and 10 percent savings were available through an aggressive leak-protection program.

In addition to correcting all the leaks, to reduce your unaccounted-for-water, you must know where all the water is going. Metering at the retail, wholesale, and system level is critical. You must know what you are using and what you are selling. The retail meters not only must be in place, they must be accurate, they must be read, and the data must be used. It is not enough to have meters if the actual users do not receive the information on a timely basis and actually receive some price signal. Without knowledge, there is no incentive for the individual user to act.

CONSERVATION AND DEMAND MANAGEMENT

Our conservation and demand-management programs look at all sectors of actual water use. Our *commercial, industrial,* and *institutional* program looks at the very large component of water use that is often neglected by conservation programs. The basic premise is that if we can provide information to users on how they might use water more efficiently, they will act upon it. The program has three facets: technical information development and exchange, direct technical assistance, and fostering changes in technology. We did a series of audits as part of our pilot program, which demonstrated that typical facilities might save 20 to 30 percent with a payback of under 3 years. We have done these audits for a few dozen users and we are now planning to move to our entire system. We feel that over the short term, 5 percent savings of total system use are possible, and as prices continue to rise we would expect even more.

Our *domestic* conservation program employs a similar strategy. We want to make users aware of water as a precious limited resource, give them a clear understanding of its real cost, and then provide a range of practical ways for them to save water. One of our most concrete programs is the installation of water-saving devices in homes. This includes shower heads, faucet aerators, displacement devices for toilets, and a household leak-detection survey. Again, we first did a small pilot of 7,000 homes and did a thorough scientific evaluation before deciding to go systemwide.

TABLE 1
Comparative Costs of Alternatives

Alternative Source of Water	Annual $/MG[1]	Capital Cost, $millions	Yield, mgd
Connecticut River	500-800	120-220	63
Millers/Tully Rivers	900	135	38
Merrimack River	1,600	600	120
Leak Detection and Repair	140	30	30
Domestic Device Retrofit	230-560	10	5-12
Low-Flow Toilet Retrofit	3,300	200	17
Local Sources	340-1,300	16	0.4-8
Water Sharing	50-500	0.2[2]	
Nondomestic Management	50		0.8_2
Sudbury Res. Treatment Plant	800	0.1[2]	0.7[2]
			16.5
FY92 MWRA Water Rate	664	34-37	
		N/A	N/A

1. Annual O&M and amortized capital costs per million gallons, 1990 dollars.
2. Yields and costs from limited experience. Actual totals will be higher but $/MG will be in the range shown.

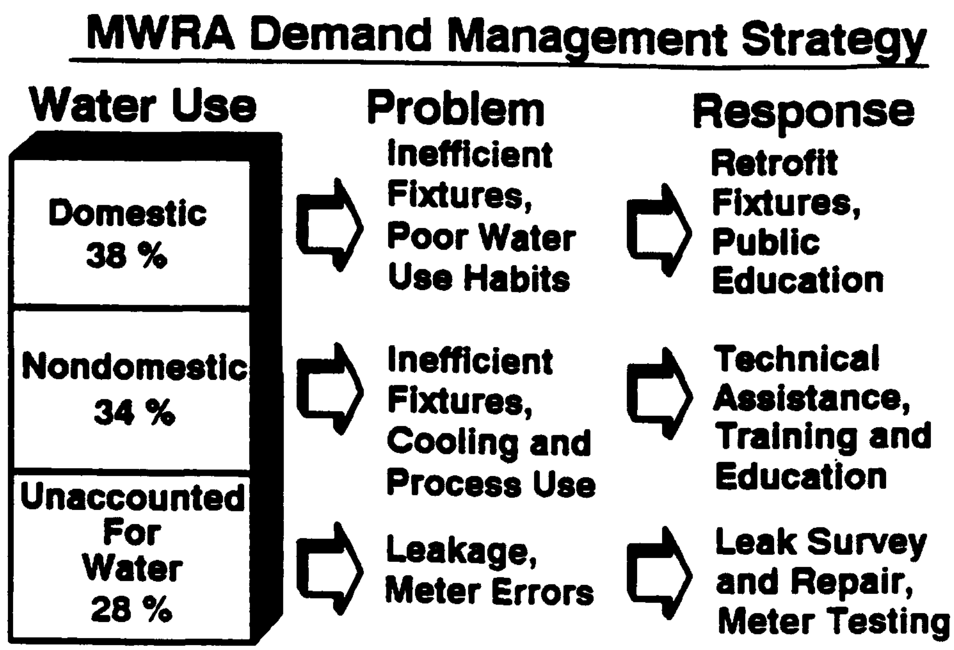

Figure 2. **MWRA demand management strategy.**

Our pilot was evaluated much more thoroughly than many have been elsewhere in the country. We did a 1-year forward and 1-year back controlled evaluation where each participating household was matched with a similar nonparticipating household, and water records were examined before and after the devices were installed. Based on that and our marketing evaluation, we believe that as we go to all 800,000 households in our service area, we will reach about 60 percent of them and save 5 to 12 million gallons per day. We are doing this for a cost of about $23 per household. We are using the direct-installation model rather than dropping devices off or simply handing them out because it is the cheapest per gallon.

One of the advantages of a thorough evaluation of the program was that we found that while it was more expensive to install the devices than it was to simply hand them out, many of the devices handed out were only installed in kitchen drawers. Those that were installed were mostly faucet aerators, some shower heads, and only a few of the most-water-saving device, the toilet dam.

All our evidence indicates that we can anticipate about 2 percent systemwide savings with a domestic device program.

We also look at changes in technology as a good way to save water in the long term at a relatively low cost to the agency. A good example of this was the 1.6-gallon-per-flush toilet code that was started in Massachusetts in 1987. Our staff went to the Plumbing Board and requested the change, and the process began. It was relatively simple. The code is now in place, and all new or rehabilitated housing requires 1.6 gallon-per-flush toilets. We anticipate that we will save about 4 percent of total water use over the next 20 years, at basically no cost to the agency.

Municipal conservation is also important, not so much for the total water it saves, but for setting and maintaining an effective example giving credibility to your program. We are looking at sprinklers and fountains, public lawn watering and other, very obvious areas, as well as interior water use from bathrooms and showers. One of the things we did to encourage the use of the 1.6-gallon toilets was to install them in municipal buildings and provide a lot of publicity.

An even longer term program is *school education*. Many utilities have tried this, typically having a staff member periodically give talks at local schools, or by providing some type of videotape or handout material. We have taken a much more long-term approach here in that we have developed curricula for various grade levels. We have a curriculum guide for third and fourth graders. for middle school children, and for high school children. They are good solid educational materials, not just propaganda. Everyone wants the teachers to teach about their issue, but teachers are interested in providing knowledge to their students, so our program was designed by educational consultants and revolves around principles of science, mathematics, and history. We provide training for teachers as well as provide resource kits that they can borrow.

Pricing is another area that is often discussed and that we believe has a firm place in any conservation program. You must send sound economic signals to users if you expect them to act rationally. In Massachusetts, we prohibit declining block rates and encourage increasing block rates. We are also working to encourage more frequent billing to provide good quality information to users. If you bill every 6 months or quarterly, by the time users receive a price signal, they have long forgotten what actions they took or did not take. Monthly bills would be our preference. It is also important to look at things like seasonal block rates. As water becomes more expensive, one of our equity considerations has been to look at lifeline rates to provide a reasonable price for a moderate amount of water. Often marginal pricing is discussed by theorists as being a useful thing to do. Our practical experience indicates that the first step is to move toward full price of the water. The next step would be full cost recovery where you are sure that all attributes of the water service are recovered by the rates. Finally, after those are done, you may want to consider true marginal cost pricing.

While we have not thoroughly evaluated the savings in municipal conservation and school education, and do not believe that there is a strong basis to predict the savings from pricing, we feel that all three are well worth doing.

SUPPLY PLANNING

In addition to examining the demand side, we have also taken a good look at the supply side, not so much to develop major new sources but to ensure that we are effectively using the water that is available to us. As mentioned above, we have our large sources that yield about 300 million gallons, but also a large number of smaller sources that yield another 80 million gallons per day. Some of these users supply part of their own demand and we supply the rest. We have been looking at something we call synergy of sources, which is a concept originally put together by Daniel Sheer. It takes a look at the fact that there are sources with long versus short response time, some that can only be used during certain seasons, some that do not have storage, and others like our system that have a large amount of storage. The "water sharing" arrangements enable us to receive more water than we might otherwise without joint operating rules.

Our long-term planning approach tries to separate the questions of what should be done, where it should done, and when it should done. By doing this, we hope to be able to understand what the best alternatives are for various classes of needs and then remove the uncertainty of demand projections. One of the things that we have been able to do is to look at what low-cost essential things need to be done now in order to ensure that we do not lose options that may be needed in the future.

CONCLUSIONS

The key question for those trying to evaluate how experiences in demand management might be applied to adaptive response to climate change is "when do we start?" This is indeed a good question. As I see it, two issues are at stake. One is the credibility of the water managers trying to demand water savings beyond what is needed now. The second is the reduction of fat; that is, the removal of any flexibility in the system because all easy savings have been had now. Given the time-value of money, and the practical considerations of "banking" savings, we at the MWRA are unlikely to propose substantial capital outlays to adapt to climate change. And while we have and will continue to make conservative decisions about facility locations and elevations, we will not make major policy decisions based on possible climate-change effects.

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ADAPTIVE RESPONSES TO CLIMATE CHANGE: DEMAND MANAGEMENT

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ABSTRACT

The high costs of and limited opportunities for increasing fresh-water supplies suggest demand management will play the leading role in balancing supplies with demands and in determining the overall benefits society derives from its scarce water resources. A combination of laws, regulations, and administrative practices that are rooted in an era when water was considered to be a free resource together with more recent regulations designed to protect and restore water quality comprise the principal framework for managing water demand in the United States. This haphazard approach to demand management results in high social costs. Moreover, the very limited ability to adapt efficiently to changing supply-and-demand conditions suggests these costs will rise over time. In comparison to the present approach to demand management, placing greater reliance on markets and prices to allocate scarce water resources appears to offer major advantages. To realize these benefits, institutional changes are required to facilitate water marketing and to introduce pricing policies that encourage conservation. The prospect of climate change adds to the potential advantages of relying more on a voluntary approach to managing water demands.

INTRODUCTION

Climate variability is a fact of life, if not the raison d'etre, for water planners. Large, unpredictable fluctuations in natural water supplies were an obstacle to settling and developing nearly one-third of the area within the original 48 states. At the start of this century, the welfare of countless people living in arid, semi-arid, and flood-prone areas depended on the continuation of relatively benign precipitation patterns. Drinking water was still a source of debilitating and deadly disease. Then, encouraged by technological advances and supportive public policies, the nation embarked on a construction program that transformed both its hydrology and its use of water. Dams and reservoirs helped tame streams that under natural conditions varied from raging, destructive torrents to a mere trickle. Millions of miles of canals, pipes, and tunnels were built to deliver water to the nation's cities, farms, and factories. The resulting water supply systems, which supported a ten-fold increase in water withdrawals between 1900 and 1975, were designed to be robust; that is, they were designed to provide reliable supplies of water under all but the most extreme climate conditions (Frederick, 1991a).

The construction projects that shaped the nation's water development and use are traditionally viewed as consistent with a supply-side approach to water planning. However, as water becomes scarce and the costs of developing new supplies increase, water development increasingly becomes a form of demand management. That is, water projects divert supplies from one (usually an instream) use to another (usually a withdrawal) use. Managing demand involves allocating scarce resources or goods among competing uses. Water demand can be managed in many ways. Laws establishing water rights and priorities of use, regulations controlling the quantity and timing of water deliveries, pricing policies encouraging conservation, and markets facilitating the allocation of scarce supplies among competing uses are all forms of demand management. Although the options are virtually limitless, whenever water is scarce (that is, when one use adversely affects the availability of the resource for other uses), some form of demand management will occur.

Historically, water was viewed and treated as a free resource and demand management was considered to be unnecessary. In the arid and semi-arid West where nature belied this view, water laws and other water institutions that encouraged offstream water use and ignored the impacts on instream use maintained an illusion of abundant and inexpensive water until recent decades. Anyone willing to invest the money and time to withdraw water from its source established rights to use it. In some cases the costs were even subsidized because providing reliable, low-cost supplies of water was a principal means of fostering the settlement and development of the West.

Ignoring the impacts of withdrawals and dams on instream use may have been reasonably efficient when offstream supplies could be developed at relatively low financial and environmental costs and when water for one use did not significantly affect the availability for other uses. Moreover, use of lakes and streams to dispose of wastes imposes few costs on other water users as long as the quantity and toxicity of the wastes do not exceed the assimilative capacity of the waters. While these conditions prevailed, the resource was not scarce and there was no need to manage demand.

Currently, however, water is scarce and getting scarcer as demand increases much faster than supply. Even in humid areas of the country and under average precipitation levels, there are competing demands for water. Under conditions of scarcity, demand management is both necessary and critical to the overall benefits society derives from its water resources. Furthermore, decisions that traditionally have been considered to involve management of supplies are likely to be a form of demand management because the total supply of fresh water is determined overwhelmingly by natural conditions rather than by human actions. Dams and reservoirs, the centerpieces of traditional water supply projects, may increase supplies for domestic, agricultural, or other offstream uses. But they do not increase the total quantity of water. Rather, these facilities and their management affect how water is allocated among alternative uses. Efficient water development and use requires accounting for the impacts of water investment and management decisions on alternative uses of scarce supplies. Contamination now represents the principal human impact on fresh-water supplies, and investments in pollution control now comprise the principal means of augmenting fresh-water supplies.

Fresh-water supplies also can be increased through waste-water recycling and desalinization. Recycling is an economically attractive source of additional water in many areas. While recycling is becoming increasingly common, its potential to supplement supplies is limited by the availability of suitable waste water and the acceptability of recycled water for some uses. Consequently, recycled water likely will remain a minor source of the nation's water supplies. Desalting is currently much too expensive for all but the most high-value uses in areas with the highest water costs. Increases in fresh-water supplies by these or other means such as cloud seeding will not keep pace with growing demands in most areas of the United States. Clearly, balancing future water supplies and demands will require some form of demand management.

WATER LAW--THE FRAMEWORK FOR MANAGING DEMAND

In a lawless society, the strongest, most clever, and determined members control the most valued resources. To avoid the chaos, uncertainty, and inequities of such an outcome, governments establish and enforce rules defining the rights to use and transfer resources. The resulting laws and institutional arrangements determine a society's approach to demand management.

There are two basic approaches to demand management. The voluntary approach relies on prices to provide incentives to conserve on use and on markets to allocate supplies among alternative uses. Clearly defined, transferable property rights are essential to the existence of well-functioning markets. Taxes (that are not confiscatory), subsidies, and other government policies that influence resource prices but allow individuals and firms to respond freely to those prices are consistent with a voluntary approach. In the absence of such property rights and markets, government commands and controls are used to limit use and allocate supplies. The regulatory approach dominates the management of water demand in all countries.

In the United States, the states reserve the right to allocate the waters within their boundaries that are not encumbered by federal law or interstate compact. Consequently, state water law is central to demand management. Water law in the eastern states is based on the common-law doctrine of riparian rights granting the owner of the land adjacent to a water body the right to make reasonable use of the water so long as it does not unduly inconvenience other riparian owners. Strict adherence to the riparian doctrine is incompatible with water marketing because the rights to the water are attached to and not transferable from the land. The right to divert water from a stream to a riparian land depends on regulatory and judicial determinations as to what constitutes a reasonable use or an undue inconvenience.

The shortcomings of the riparian doctrine for allocating limited water supplies led the western states to develop and adopt the doctrine of prior appropriation, which establishes the principle of first in time, first in right as the basis of their water laws. Appropriative water rights are created by diverting water from a lake or stream and putting it to a "beneficial" use. The appropriation doctrine breaks the link between water rights and land ownership, eliminating a major obstacle to establishing transferable water rights. However, the use and marketability of these rights commonly are limited by a variety of legal provisions. Undefined beneficial-use provisions cloud the nature of a water right and the legality of selling water. A number of states have specific demand-management provisions in their codes that further restrict and confuse water rights. For instance, a water right might be restricted to a specific use and place. Or preferential-use provisions, which exist in 12 states, allow the rights of nonpreferred users to be condemned during periods of scarcity.

Both statutory and case law and administrative decisions that control the allocation and use of water have evolved over time in response to changing supply-and-demand conditions. Among the more important changes of the past two decades are those providing protection for instream flows and lake levels. The prior-appropriation doctrine contributed to the depletion of western streams by rewarding those who acted quickly to divert these waters. And the virtual free and uncontrolled use of water bodies for the disposal of wastes left many of the nation's streams and lakes too polluted to support most instream uses. Both state and federal laws have been altered to counter these abuses. As of 1988, New Mexico was the only western state that had not either legislatively or administratively taken steps to protect some of its remaining streamflows (Shupe, 1989). Both state and federal laws have designated some streams as wild and scenic, effectively removing them from any major water development and diversion schemes. Some state agencies have been empowered to establish water rights to maintain streamflows and lake levels. And in a few situations, these agencies have purchased senior water rights where the appropriation of junior water rights would not adequately protect instream values. Although most western states prohibit the private sector from appropriating instream rights, environmental groups have argued (successfully in the case of Mono Lake in California) that the state's obligation to protect important public values provided by natural water bodies can override previously issued rights to divert those waters. The National Environmental Protection Act of 1969, the Federal Water Pollution Control Amendments of 1972, and a host of subsequent environmental legislation reflect the federal government's strengthened commitment to protecting instream values.

Most of the recent legislative changes initiated in response to changing water values, increasing water scarcity, and deteriorating water quality fall within the command-and-control approach to demand management. However, several states have modified their laws and regulatory activities to facilitate voluntary water transfers. California has passed legislation declaring water marketing to be a beneficial use, and in 1976-1977 and again in 1990-1991 the state established an emergency water bank to help allocate drought-diminished supplies. Oregon has passed legislation permitting the sale of conserved water. And a Water Exchange Information Service has been formed in Colorado to provide information for buyers and sellers of water. These are just some of the changes that have helped make water marketing increasingly common in the West during the past 5 years or so.

Markets and Prices

Although markets and prices are the primary means for allocating scarce resources among competing uses in the United States, their use for managing water demand remains the exception rather than the rule. The relative absence of water marketing is due in part to the continued dominance of institutions and water management practices that are the product of an era when water was viewed as a free resource. Traditionally, water planners assumed that municipal, industrial, and other offstream demands for water would grow virtually in step with population and income. The resulting projections of water use were treated almost as requirements to be met regardless of cost.

Water prices were assumed to have no significant impact on municipal and industrial use, and average-cost pricing was used to keep prices as low as possible and to prevent water suppliers from reaping monopoly profits. Municipal and industrial water prices generally were set high enough to cover the costs of delivering and treating water, but there was no charge for the water itself. Even these prices were too high for many irrigators, and federally supplied irrigation water has been highly subsidized.

Under the present conditions of water scarcity, it is appropriate to consider what role markets and prices can or perhaps should play in adjusting to changing supply-and-demand conditions. When they function well, competitive markets and prices result in an economically efficient allocation of scarce resources. Prices provide producers with incentives to increase or decrease output and consumers with signals to consume or conserve. The interaction of supply and demand determines the equilibrium level of prices in a competitive market. When supply exceeds demand, price declines encourage less production and more consumption. Alternatively, when demand exceeds supply, higher prices encourage production and discourage use.

Efficient markets require that there be well-defined, transferable property rights in the resource to be traded and that the full costs and benefits of using or exchanging the resource be borne by the buyer and seller. The nature of water resources makes it difficult to satisfy these conditions. First, it is difficult to establish clear property rights over streams and groundwater resources that flow from one location to another. Second, when ownership is established only by capture and extraction, the individual does not bear the full costs of using the resource. Externalities or third-party effects also are common when water is transferred to an alternative use or when water is used for disposal of wastes. Third, water resources provide public as well as private goods. A public good such as the vista provided by a free-flowing stream is not marketable because nonpaying individuals (free riders) cannot be excluded from enjoying its benefits. Consequently, society under-invests in public goods when the supply is left to market-based incentives (Frederick, 1984).

The monopolistic nature of the water supply industry also presents problems for introducing efficient pricing. Water is often supplied by public agencies or regulated private monopolies. Efficiency of production and consumption is achieved when the marginal value in use (that is, the price to the consumer) is equal to the marginal cost of the last unit produced. The marginal costs of developing new supplies for offstream use are rising sharply in most areas (Frederick, 1991a). Efficient pricing practices in such an industry would increase price to reflect the cost of bringing on line the last and most expensive supplies. Marginal-cost pricing would curb use and reduce the demand for additional, more expensive supplies. When the marginal cost equals the price consumers are willing to pay, the marginal value of the water is equal to the marginal opportunity cost of the resources used to produce it. In a water-scarce region, the value of the water in alternative uses is likely to be an important component of these opportunity costs.

The same principles apply to investments in water conservation. It pays to conserve when the marginal costs of conserving a unit of water are less than the marginal value of the water as determined by its market price (Frederick and Kneese, 1990). Marginal-cost pricing gives consumers the appropriate signals to conserve.

Balancing Voluntary and Regulatory Approaches

Although the ideal of efficient markets and prices may be unattainable, the shortcomings of a voluntary approach to demand management appear less imposing when compared to the costs associated with the regulations currently used to allocate water and to control its use and abuse. For instance, the opportunity costs to society of locking large quantities of federally subsidized water into agricultural uses that have adverse environmental impacts and contribute to crop surpluses are high. Allowing water that is now supplied to irrigation districts in California at subsidized prices (often at $15 per acre-foot or less) to be transferred voluntarily to urban uses might provide irrigators incentives to conserve water and eliminate the demand for some new water projects projected to cost from about $300 to more than $1,500 per acre-foot.

The opportunity costs of water also can be high when a water system is managed according to historically determined guidelines that fail to account for changing water values. Navigation continues to receive a high priority in the operation of the Corps of Engineers Missouri River reservoir system even though it requires large quantities of water and accounts for less than 2 percent of the total benefits provided by the six reservoirs. Preliminary results from an ongoing review of the operating criteria for these reservoirs suggest that average net national benefits of the system might be increased by as much as $97 million per year by placing higher priority on providing minimum winter and summer flows for the water supplies of downstream communities and by increasing the size of the permanent pool in the reservoirs to increase hydropower and recreation benefits within the upper basin (U.S. Army Corps of Engineers, 1990).

The high costs of the regulatory approach adopted to meet water quality objectives have stimulated interest in the possibility of introducing market-based incentives to promote environmental values. Water pollution control costs (in 1986 dollars annualized at 7 percent) increased from about $9.9 billion in 1972 to an estimated $42.4 billion in 1990. About 92 percent of these costs was incurred in response to federal mandates (U.S. EPA, 1990b). Although these expenditures have contributed to major improvements in the quality of many streams and lakes, data collected by the states in 1986 and 1987 indicate that water quality in 30 percent of the assessed river miles and 26 percent of the assessed areas of lakes and reservoirs was inadequate to fully support the designated uses of these waters (U.S. EPA, 1990a). Under existing regulations, water-pollution-control efforts will continue to be directed primarily to reducing and treating industrial and municipal wastes (that is, point-source pollutants); the annual costs of these efforts are projected to increase to $58 billion by the end of the century (U.S. EPA, 1990b). However, investments in controlling point-source pollutants are encountering diminishing returns in restoring the remaining waters to a fully usable status.

Nonpoint sources such as runoff from farms, urban areas, and construction sites and seepage from landfills and septic systems are now the principal polluters of the nation's waters. Irrigation is a major polluter of surface waters in some areas of the country, and federal policies such as the provision of subsidized water and crop price supports have aggravated the water quality problems associated with irrigation. Regulation of irrigation practices to achieve water quality objectives is likely to be very inefficient unless the regulations can be readily tailored to the wide diversity of farm-level and water quality conditions. Market approaches such as charging irrigators water prices that more nearly reflect the full costs of their water use or introducing effluent charges or marketable discharge permits would provide incentives to reduce water use and return flows. The combination of higher water costs and improved opportunities to market unused water would have the dual benefit of improving water quality and helping to meet the overall demand for water in some of the nation's most water-scarce regions (Frederick, 1991b).

Markets work best when supply and demand are elastic (that is, when small percentage changes in price produce large percentage changes in the quantities supplied and demanded. Both supply and demand tend to be more elastic as the time for adjustment increases. In the very short term, it may not be possible or feasible to develop new supplies, to invest in conservation measures, or to adopt new practices in response to higher water prices. Over the longer term, more wells and dams can be constructed; fewer water-using crops or seed varieties and more efficient irrigation technologies can be introduced; water-conserving showers, toilets, and appliances can be installed; and thermoelectric power plants can shift from wet- to dry-cooling technologies.

The short-term inelasticity of supply and demand support the use of regulatory measures to limit use during periods of extreme drought. Drought responses often start with appeals for voluntary conservation measures. If conditions continue to deteriorate, nonessential water uses such as watering lawns and washing cars and sidewalks are apt to be banned and businesses may be required to reduce use by specified percentages. The magnitude of the price increases that would be required to bring demand voluntarily into line with drought-reduced supplies likely would be politically unacceptable. A tiered-pricing policy that maintains a low price for some minimum level of use and imposes sharply higher prices for additional water might satisfy the objections to higher prices based on equity concerns while providing large users with incentives to conserve. Avoiding any price increase and relying entirely on regulatory measures to curb water use during periods of drought may leave a supply utility with insufficient revenues to cover its costs.

The command-and-control approach also is being employed to curb the long-term growth of water demand. A number of states and local communities have followed Massachusetts in passing legislation requiring the use of water-conserving toilets and shower heads in all new construction and remodeling. Moreover, both branches of Congress are considering legislation that would establish national water conservation standards for the manufacture and labeling of certain plumbing products. Relying on regulations such as technology-based standards to alter long-term demand is likely to be less efficient than introducing price incentives. Proponents of legislatively mandated standards argue that regulations are necessary to ensure that manufacturers produce water-conserving products in sufficient quantity to achieve economies of scale. A less compelling argument for product standards is that low water prices provide consumers with insufficient incentives to purchase water-conserving products. This latter argument can be turned around to support the introduction of marginal-cost pricing and the use of price incentives to encourage voluntary adoption of water-conserving measures.

The State Water Conservation Coalition--a California group including urban water agencies, environmentalists, and elected officials--has spent the last 4 years studying and negotiating a water conservation program. Their proposed program includes a mixture of regulatory and incentive measures. The regulatory approach would be used to prohibit car washes, commercial laundries, and decorative fountains that fail to recycle and to prohibit the installation of toilets using more than 1.6 gallons per flush. Commercial, industrial, institutional, governmental, and multi-family residences would be required to use water-conserving landscaping, and construction permits would not be released without a water-efficiency review. The voluntary approach would be pursued by adopting pricing policies designed to encourage conservation, by providing rebates for replacing old toilets with ultra-low flush models, and by introducing educational programs promoting conservation. The proposed pricing policies would depend on billing by volume. Consequently, meters would be required for all new connections and whenever a property is sold (Muir, 1991). Notable shortcomings of the California water coalition and its proposed conservation program are the absence of agricultural interests among the coalition and the failure to address irrigation water use, which accounts for about 91 percent of the state's consumptive use and 82 percent of its fresh-water withdrawals (Solley, Merk, and Pierce, 1988).

CONCLUSIONS

Demand management is not just a substitute for water supply projects. Most supply projects involve demand management because they require tradeoffs among water uses. The opportunities for increasing supplies without such tradeoffs are either too costly or otherwise too limited to provide for more than a small fraction of the growing demands on water. Historically, the tradeoffs often were made by ignoring many of the adverse impacts on instream water values. However, rising environmental values and recent legislation protecting these values essentially have eliminated this myopic approach to demand management.

Effective demand management requires a careful balancing of efficiency, equity, and environmental objectives as well as of the desires and rights of competing interest groups. Moreover, it requires balancing the relative advantages of voluntary and regulatory approaches. In contrast, current demand management occurs more by neglect or accident than by design. Policies that were designed when water development was valued as a means of providing jobs and encouraging settlement of the West together with more recent regulations to protect and restore environmental values play a dominant role in the use and allocation of the nation's water resources. The result is a haphazard approach to demand management with limited ability to adapt effectively to changing supply-and-demand conditions for water. While the benefits of relying more on a voluntary approach to demand management appear great, major changes are required to establish the well-defined, transferable water rights that would facilitate water marketing and to introduce pricing policies that would encourage conservation.

The possibility of a greenhouse-induced climate change adds uncertainty as to the future availability of and demand for water. Although a greenhouse warming likely would have major impacts on regional hydrology, the magnitude and even the direction of the changes on particular regions are unknown (Frederick and Gleick, 1989). While the robustness of the water supply systems provides a hedge against the uncertainties of climate variability, these systems as well as current management practices and patterns of use are based on the existing climate. The infrastructure almost certainly would be less well suited to a new hydrologic regime, but investments in new infrastructure would be very costly and perhaps of little value in view of the enormous uncertainties as to the nature of the hydrologic impacts. On the other hand, institutional changes that would enable scarce supplies to be reallocated efficiently over time in response to changing supply-and-demand conditions would facilitate adaptation to climate change regardless of its hydrologic impacts. Accordingly, the prospect of climate change reinforces the case for developing improved approaches to managing the demands for water.

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THE NEED FOR FLEXIBLE WATER SUPPLY INSTITUTIONS TO RESPOND TO CLIMATE CHANGE

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ABSTRACT

Any long-term climate change will necessitate increased flexibility on the part of our institutions for managing and allocating water. One promising vehicle for providing flexibility is voluntary water marketing. The prices from such transfers can serve both as price signals to current users, which should affect their demand, and as a signal to potential purchasers. Administered pricing is another alternative to promote demand management. Various examples of water transfers and administered pricing in the western United States will be discussed, including their limitations and recommendations for change.

INTRODUCTION

The current state of general circulation models is such that we really cannot draw any definite conclusions from them on a regional basis. As far as the western United States is concerned, some climate models in the past have predicted decreased precipitation. More recently, others are predicting somewhat wetter conditions. But, in either case, higher temperatures may well mean that spring runoff will occur over a shorter time period and therefore be harder to store, at least with our existing facilities. Any decrease in water delivered through storage and distribution systems could well occur simultaneously with increased human demands for water, be they agricultural or domestic. And, of course, water for natural ecosystems should be part of the picture also. Therefore, in the western United States, it appears that our chief concern would be decreased, rather than increased, water availability. Is this situation a cause for alarm? What should we be doing about it? And what is the potential role of demand management?

To put the potential response strategies in the proper framework, this paper addresses a somewhat broader range of measures than demand management. The conclusions of the IPCC report on response strategies for water resources (IPCC, 1990) are, in brief, the following: (1) We should be generally conservative at this point in our reaction to climate change, (2) given the uncertainties, we should undertake measures that are cheaper, such as water conservation and demand management, rather than more expensive, such as additional construction, and (3) as a hedge against the risk of climate change, we should undertake these measures sooner, rather than later. Underlying these conclusions is an observation that there is a lot we can do to improve our efficiency of water use, even in the absence of climate change, and that we should get about it.

As noted by Peter Rogers in his paper in this volume, with any reasonable discount rate, the benefit of undertaking activities now, such as construction, which are further than 15 years away, do not justify large costs. Put another way, you would have to be relatively certain that large changes were going to occur in the near future (and the direction and magnitude of the changes) before committing construction funds. With that background, let me address some of the possibilities for efficiency improvements and the ability of our institutions to accommodate them.

The nearest current analogue to the conditions that would be of most concern to the western states is long-term drought. One of the recurring proposals to deal with drought is to do more to promote water conservation. This recommendation, however, appears to me to be largely flawed if considered in isolation. Underlying the conservation proposal is the premise that conservation will provide us extra water during a drought. Also, environmentalists calling for conservation assume that this water would stay in the stream--to be used for protecting fish and wildlife habitat. However, additional water availability during a drought may not be a necessary consequence of conservation. In particular, while conservation may provide extra water in the near future, it is not the full answer in the long run. The reason is that under western water law, conserved water becomes available to other appropriators. Under some state laws, conserved water could be sold to another appropriator. If it is not sold or transferred, then it becomes available to junior appropriators, so it does enhance the probability that they will receive deliveries in times of drought. Finally, any extra water can go to new appropriators, albeit at the end of the priority chain. But once those increases are taken into account and relied upon in terms of population growth or farm investments, they do not necessarily guarantee flexibility during a drought or other crisis.

Conservation is not enough because if the conserved water gets reallocated, a water storage and delivery system can be just as constrained as before the conservation took place. What is needed is not just conservation, but a system of institutions that can be flexible in allocating water during a drought. Let me discuss two measures that promote such flexibility--markets and drought contingency plans.

Voluntary Water Markets

One means of providing flexibility during a drought is to allow voluntary reallocation, and one way of doing this is through markets (Saliba and Bush, 1987; Wahl, 1989). Markets allow decentralized decision-making, which allows the ingenuity of local water managers to be tapped, as well as the ingenuity of almost every water rights holder. Markets can respond by pricing water based on the severity of the shortage, its geographical extent, and possible alternative sources of supply. Similarly, when there is a freeze of citrus crops, the futures prices of oranges rise, without the need for some centralized decision-maker to set them. Price is simply a function of supply, demand, and substitutes. If market forces were really working to help us allocate water supplies, then, when drought is projected, water prices would respond and people and businesses would adjust their water use decisions accordingly. Higher prices would mean more careful use, switching to substitutes, and less total consumption. Among the substitutes for water are the additional labor required for more careful use, capital investment in water conservation measures, and recycling. In short, the more practice we can get with marketing, which is a fledgling institutional development in most parts of the West, the better off we will be during a drought. Of course, in revising our institutions to facilitate market transactions, we should do so in a way that will not ignore the water uses that are traditionally not marketed, such as instream flow for maintaining fish and wildlife habitat (Wahl, 1990).

Perhaps the most dramatic recent examples of water transfers in the West are the agreements reached between the Imperial Irrigation District and the Metropolitan Water District of Southern California (MWD). Imperial diverts about 3 million acre-feet annually of Colorado River water, which represents nearly 25 percent of the total diversions from the river. In the fall of 1988, Metropolitan and Imperial reached an agreement under which Metropolitan will pay Imperial to fund conservation measures within the irrigation district that would salvage 100,000 acre-feet of water annually for diversion to Metropolitan's service area. Metropolitan will pay Imperial $92 million for construction of the conservation facilities, $3.1 million annually for operation and maintenance, and $23 million in five annual installments for indirect costs. The same two entities reached a separate agreement under which Metropolitan can fund lining of the earthen All-American Canal (a federally constructed facility that transports water from the Colorado River to the irrigation district) in exchange for the conserved water. Both state and federal studies indicate that there is potential for another 200,000 acre-feet of conservation within Imperial, which may provide the basis for future agreements between the two entities (Wahl and Davis, 1986).

And there are many other examples of water transactions where the amounts of water transferred were smaller. Annual rentals of water from the federal reservoirs on the Upper Snake River date back to the 1930s and are explicitly recognized in Bureau of Reclamation contracts with water users. In 1972, the Utah Power and Light Company obtained 6,000 acre-feet of water from two irrigation companies in the federal Emery County project for power plant cooling. During the 1976-1977 drought in California, the Bureau of Reclamation operated a water bank in which some 45,000 acre-feet of water changed hands for total payments of $2.2 million. The city of Casper, Wyoming, is paying the nearby Casper-Alcova Irrigation District for canal lining on portions of the district's 59-mile canal and 190-mile lateral system in order to reduce seepage. The exchange is intended to provide the city with 7,000 acre-feet of water. One of the most notable examples of a functioning water market is in the Northern Colorado Water Conservancy District around the Fort Collins area, where shares of Colorado Big Thompson Project water have, for years, been sold at market value (Wahl and Osterhoudt, 1986). More recently, BMI corporation in southern Nevada transferred an additional 9,000 acre-feet of Colorado River water to the growing town of Henderson (for more detail on this and other recent transfers, see MacDonnell, 1991).

The Bureau of Reclamation will have an important role in facilitating water transfers because of its extensive facilities in the West. The bureau supplies about 27 million acre-feet of water for irrigation annually; about 3 million acre-feet for municipal and industrial use, and about 1 million acre-feet for other uses. Irrigation water is delivered to about 10 million acres of farmland. Although this represents, on average, only about 20 percent of the irrigated acreage in these states, the bureau delivers water to more than 40 percent of the irrigated acreage in some states. These figures may under-represent the potential importance of the Bureau of Reclamation in water transfers since the bureau controls major storage and conveyance facilities in several states (such as the Central Valley Project in California and the Central Arizona Project). In December of 1988, the Department of the Interior adopted a set of principles to allow trades of water that is under contract to the Bureau of Reclamation. This policy also allows an economic incentive or profit on the water, provided the costs required by reclamation law are paid. This policy is designed to lower the uncertainty that surrounded previous bureau transfer policy, which varied from one project to another.

Contingency Planning

Another source of flexibility during prolonged drought is contingency planning. First, under current climate, systems analysis of multi-reservoir systems should be undertaken in order to simulate and then take advantage of joint operational efficiencies (Sheer, 1986). In particular, it would be important for such planning to cross normal jurisdictional boundaries within a river basin and to include federal, state, and local facilities. Then, if the entities involved want to test the resilience of their supply system to drought or climate change, they could simulate various scenarios of reduced (or increased) runoff. We all know how time-consuming agreements can be in the water supply area. Therefore, it would be important for those involved in operating these reservoirs to work out in advance how they would respond.

Markets and Demand Management

What do markets have to do with demand management? Markets are a way of providing supply: water tied up in low-value uses is made available, through market transactions, to other uses. But markets have two sides, they also provide price signals to the sellers, which should affect their demand for water. In fact, in the American West, this is, I think, one of their greatest benefits, at least on federal projects.

Markets will raise the effective cost of water to farmers, not directly through raising water rates, but indirectly because farmers must take into account what economists would call the "opportunity cost" of the water provided to them. When a farmer places water to a use returning $15 per acre-foot, or holds extra water as insurance that may return $5 per acre-foot, he must think twice if other local entities are willing to offer him $75 or $100 per acre-foot for the same water. This is the type of demand management that markets will bring. This management tool is particularly useful on federal projects, where irrigation water is heavily subsidized (often 85 percent or more of capital costs are subsidized) and where there is little contractual or legal flexibility to raise water rates.

But I do not want to place the entire burden of my remarks about markets and demand management on the agricultural sector. Pricing needs to play a greater role in demand management in the supply of domestic and industrial water. The standard enemies of efficient use here are water supply systems in which either (1) water rates are not based on the amount of water used or (2) most revenues are recovered through property taxes, rather than through water rates. For example, until 1950, over 80 percent of MWD's revenues were from property taxes. In 1960, the percentage was about 60 percent and in 1970, 50 percent. The percentage has fallen since that time and MWD expects to decrease this percentage still further (MWD, 1990).

MWD has instituted a number of interesting measures to cope with droughts, some in the 1977-1978 drought and more during the drought beginning in 1988 and lasting to the present (MWD, 1990). For example, MWD has instituted a 100 percent surcharge on entities that exceed 90 percent of historical use. MWD also has interruptible and firm water rates; in times of shortage MWD can cut off water under the interruptible contracts. However, MWD faces one major problem in instituting more efficient measures, such as pricing based on long-run marginal costs: namely, MWD has little or no influence over the water rates charged to final consumers. MWD sells water to 27 member agencies--some 14 cities and 13 districts that encompass several cities each. MWD does not control the rate structures under which its member agencies sell water. By one estimate, in some cases as little as 20 percent of an MWD price increase gets passed down to the ultimate consumer. Clearly, there is a lot of room for improvement in water pricing within institutions such as these.

It is important that western cities gain more experience with commodity charges for water and that they be able to employ them in drought situations. Water markets are not going to be really efficient until marginal cost pricing operates down to the level of the final consumer, not just at the level of water districts.

Responses to Severe Conditions

Finally, let me address one concern that some readers will have. Even though they may grant that the points made here concerning water markets and pricing are plausible, that prices can guide water user behavior to some extent, and that markets can provide some "additional" water through reallocation, they may question whether markets can help much if we get hit by a very severe reduction in water supplies due to climate change. A more immediate formulation of this question is "What good is it to talk about market reallocation of water in California during a drought if you don't have any water to reallocate."

One answer is that you always have some water to reallocate, and we can point to California's institutionalizing a water banking operation during the current drought as evidence of the interest in market reallocation. Markets and contingency planning ought to be used because they will allow as much flexibility and promote as much efficiency as possible and will allow things to stay about where they are now for a long period of time. After all, water is usually a very small part of industrial costs, even for thermal power plants, and a very small part of household budgets. Water costs are even a relatively small part of agricultural production costs, although agricultural producers are more vulnerable.

Of course, if conditions in the American West or Southwest really get severe, markets will not solve everything. Not everything can stay the same, even with more efficient use. I think that if conditions are severe over a long time period, we will see migration of crop production. Any such migration will probably be gradual and may be almost imperceptible at first. It will likely occur through numerous individual decisions to change a lifestyle or to relocate. I do not think we should be alarmed, however, because we have been witnessing that kind of change for several decades now in response to other economic and social factors. One only need drive through the American West to see many abandoned farming enterprises.

A more contemporary example is the transformation of agriculture we are witnessing in parts of the High Plains area, the southern parts of which are simply running out of economically recoverable groundwater and which will return to dryland farming. Studies of the High Plains problem showed that the costs of importing water from the Missouri River system to maintain irrigated agriculture would be prohibitive (U.S. Department of Commerce, 1982). Capital costs were several hundred dollars per acre-foot, ranging up to $600 per acre-foot, on an annualized basis. Operation and maintenance costs, including large pumping costs to raise the water to the level of the High Plains, would raise the costs even higher. These costs could be compared with agricultural returns in the neighborhood of $35 to $45 per acre-foot. The cost of keeping our productive crop activities in the same location, in the face of severe climate change, would simply be too high.

In the meantime, however, there is a lot of work that can be done. We have only begun to tap our opportunities to employ markets, pricing, contingency planning, and other efficiency improvements.

Note: The views expressed in this paper do not necessary represent any official positions of the U.S. Department of the Interior.

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ADAPTIVE RESPONSES: SUPPLY DEVELOPMENT/ MANAGEMENT SESSION

Rick Gold, Chairperson
Lew Moore, Rapporteur

This session included four speakers whose presentations ranged from preliminary appraisals of climate-change consequences to the hands-on experience of managing a water system with dynamic demands and constraints. In this session, Mr. Darrell Bakken gave concrete examples of how a public drinking water system must adapt to dynamic conditions (Minimizing the Effects of Climate Change on a Public Water Supply Utility's Sources of Supply); Dr. Kathleen Miller amplified the Colorado Front Range example with her presentation of the search for alternative water resources (Property Rights and Groundwater Development in a Changing Climate: A Case Study); Dr. Steven Rhodes presented an analogue to hypothetical global-change supply scenarios in his paper (Planning for Municipal Water Supplies with a Future Climate Change: The Two Forks Veto as an Analogue); and Dr. Kenneth Strzepek spoke about projections of hydrologic impact of global change in the Nile and Zambezi basins of Africa (Water Supply Development in Response to Global Climate Change: Case of the Nile and Zambezi Rivers).

The recorders of the Adaptive Responses Seminar were asked to focus on common themes in the presentations that addressed the following questions: (1) what ought to be done today, (2) what are the key impediments to adaptation/implementation strategies, (3) what innovative solutions should be considered in the next 5 to 10 years, and (4) what research/knowledge gaps mentioned prevent us from making good decisions?

Actions for Today

From the "no regrets" perspective (courses of action that will help regardless of future climate contingencies), the presentations revealed several courses of action that appeared to be justified now: Darrell Bakken demonstrated how long-term comprehensive planning, coordinated operations, and a recent engineering study had allowed the Indianapolis Water Company to expand service and even "discover" new water supply in an existing system; Kathleen Miller cited the need for groundwater model development in Colorado as a prerequisite for any eventual solution to the present fracas over exportation of groundwater from the San Luis Valley; and Ken Strzepek identified acceleration of water project development on the Zambezi as being advisable for future flexibility.

Key Impediments to Adaptation/Implementation Strategies

Identification of key problems was fairly clear in all the presentations: Strzepek's analysis illustrated the wide disparity of results in applying the various general circulation model (GCM) outputs to hydrologic modeling. Similarly, Miller's conclusion on potential massive groundwater withdrawals was that there is no winner in the "war of the groundwater models"; moreover, Rhodes' synopsis was that no consensus for future Denver-area water supply had developed primarily because the issue had not been galvanized by a real water crisis.

Innovative Solutions for the Next 5 to 10 Years

Because of the diversity of subject matter and methodology of the papers, solutions ranged from the enigmatic to the obvious: Ken Strzepek's study showed that more tool development and refinement of projections is required before any mitigation measures other than the "no regrets" approach (see title (1) above) could be recommended. Similarly, Kathleen Miller's prescription was to make more resources available to the State Engineer to refine water models so that some "official state" conclusions on the effects of groundwater withdrawals could be drawn. Steven Rhodes cited a "water sharing" proposal being offered by the Northern Colorado Conservancy District as one possibility for ameliorating the coming water shortage for many Front Range municipalities. Darrell Bakken's presentation further confirmed that public involvement and long-term planning were essential and continuing processes--even in humid climates.

Research/Knowledge Gaps That Prevent Good Decision-Making

The speakers were fairly concise in identifying gaps in basic knowledge that are frustrating or could frustrate mitigation and response strategies directed toward mitigation of global-change effects: Ken Strzepek stated that the range of disparity in GCM output must be reduced; presently his range in projections of Nile River flow with doubled carbon dioxide ranges from a 46 percent decrease to a 62 percent increase, depending on which GCM output is used. Likewise, Kathleen Miller illustrated the political consequences resulting from lack of understanding of the deep aquifers of the San Luis Valley. Nevertheless because the stakes are so high (Denver is willing to pay $6,000 per acre-foot for permanent water rights), some bounding of the uncertainty is required. Steven Rhodes' effort to project a solution to the Denver water supply problems are frustrated by a breach in the reasoning process between environmental interests and water managers/developers; because no forum for resolution of these issues exists (the parties have not yet begun to suffer actual shortages), no dialogue seems to be developing between opposing interests. Finally, from a more-applied-science setting, Darrell Bakken's future concerns for the Indianapolis water supply were directed at the adequacy of groundwater monitoring, preventing contamination of aquifers, and being able to anticipate changes and their consequences from new legislation and amendments to both the Clean Water Act and the Safe Drinking Water Act.

In summary, this session provided examples of the extremes in climate-change studies, from the first-cut appraisals of the Nile and the Zambezi in Africa to the tweaking of an established municipal system in Indianapolis. Most intriguing, however, was the Rhodes/Miller analogy that gave insights into how society may choose to deal with (or ignore) the possible consequences of climate change.

MINIMIZING THE EFFECTS OF CLIMATE CHANGE ON A PUBLIC WATER SUPPLY UTILITY'S SOURCES OF SUPPLY

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ABSTRACT

The Indianapolis Water Company (IWC), an investor-owned water utility serving a population of approximately 750,000 people in central Indiana, has recently undertaken efforts to minimize the potential effects that climate change might have on its surface and groundwater supply sources. By reanalyzing storage volumes and safe yield of the two company-owned reservoirs in a major engineering study, and by a corporate commitment to future planning that includes (1) accurate estimation of future water supply needs of the Indianapolis metropolitan area, (2) development of a conjunctive use model to maximize yield and dependability of existing surface-water supplies and existing and future groundwater resources, and (3) preparation of a comprehensive water shortage plan, the utility stands ready to respond to a change in climate that otherwise might have serious repercussions for the Indianapolis area.

INTRODUCTION

The long-term reliability of a public water supply depends on several elements, including changing demands of its service area, dependable yield of its supply sources, maintenance of pumping and distribution infrastructure, and the reliability of precipitation and runoff. The Indianapolis Water Company, an investor-owned utility serving approximately 750,000 people in central Indiana, has undertaken a comprehensive evaluation of the future water supply needs of its service area and a review of the multiple sources of supply used by the utility. In addition, the company is developing a water shortage plan (not strictly a drought plan) that can help management and operations personnel react rationally to diminished water supply availability. While climate change is one consideration in the overall effort, there are a number of other factors that must be considered by a water utility as it evaluates its ability to provide adequate water for its customers.

One part of IWC's study provided the company with up-to-date surveyed and recomputed water supply storage volumes of the two reservoirs owned by the company and engineering reports on the safety of both of the dams that impound those reservoirs. The results of the study have made it possible for IWC to construct a new water treatment and pumping facility that will use additional calculated yield from one of the IWC reservoirs; an added yield that was previously unknown. In addition, IWC has embarked on multiple groundwater development projects that we trust will allow for substantially greater flexibility in managing available water supply sources in times of drought or through cycles of climate fluctuation.

DEVELOPMENT OF A WATER SUPPLY SYSTEM

The Indianapolis Water Company and its predecessor (Giffin, 1981) have furnished public water service to the city of Indianapolis and adjacent areas since 1871. From 1881 to 1947, IWC grew along with the city into a compact urban utility. Since 1947 the water utility has expanded through marketing and acquisitions to a regional system that provides retail water service to most of Indianapolis and Marion County, as well as portions of four adjoining counties. The population served by IWC has increased from about 445,000 in 1947 to approximately 750,000 by the end of 1990. Daily average water consumption increased from 49.7 mgd (188 X 10^6 L/day) in 1947 to a peak of 120.5 mgd (456.7 X 10^6 L/day) in 1988. The maximum peak-day demand on the system totaled 202.3 mgd (766.7 X 10^6 L/day) and occurred on August 2, 1991.

Water service in Indianapolis began with two wells and a pumping station located in what is now downtown (Bakken, 1981; Stout and Bakken, 1973). The pumps were powered by water flowing through the former Indiana Central Canal, purchased by the utility in 1871. IWC purchased the water system in 1881 and within a few years acquired near-downtown land that is now the location of the utility's general offices, a primary pumping station, and another well field. Prior to construction of the well field, a horizontal infiltration gallery was constructed on the near-downtown site. By the 1890s, problems with the gallery and wells led IWC to question whether groundwater could be a dependable long-range primary water source. In 1896, consulting engineer Allen Hazen recommended that surface water become the system's primary source of supply. He proposed that the White River, which bisects Marion County, be used as a source of supply and that the raw water be treated at a water treatment plant, using slow sand filtration, to be located 1 mile northwest of the center of the city (see Figure 1). The White River Treatment Plant, which today still serves as the foundation of the IWC system, was originally placed in operation in 1904. In addition to tapping White River as a source of supply, IWC acquired a dam and grist mill on Fall Creek in 1900 to obtain access to surface water on that tributary of White River.

A 1921 study by engineering consultants Metcalf & Eddy (1923) evaluated the future water needs of Indianapolis and ultimately recommended that two reservoirs be built in the ensuing 25 to 30 years. One of these reservoirs was to be located on Fall Creek northeast of the city and the other on the White River watershed north of Indianapolis.

Acquisition of land for the proposed Fall Creek Reservoir, which later became Geist Reservoir, began in the late 1920s, with the reservoir ultimately completed and filled on March 17, 1943. Geist had an original estimated capacity of 6.9 billion gallons (26.2 X 10^9 L) of water and its initial surface area at full reservoir pool was 1,900 acres (770 hectares). Total land acquisition and construction cost was $2.5 million.

Morse Reservoir, located on Cicero Creek, a White River tributary located north of Indianapolis in Hamilton County, and also recommended in the original Metcalf & Eddy report (and reaffirmed in a separate 1947 study by another outside consultant), was completed and filled on February 25, 1956. Morse Reservoir had an original capacity, as estimated by the design consultant, of 6.9 billion gallons (26.2 X 10^9 L) and an initial surface area of 1,500 acres (608 hectares). Land acquisition and construction costs totaled $6.5 million.

In 1957, after completion of Morse Reservoir, IWC selected consulting engineer C.C. Chambers to conduct a site study for a third reservoir. This study was confirmed in 1958 by an independent review (Alvord et al., 1958) conducted by three engineering consultants, Abel Wolman, Samuel Morris, and Louis Howson. They recommended the construction of a reservoir on Mud Creek, a tributary of Fall Creek, that was to be completed in the 1970s.

In the meantime, as a result of a flood in 1958, the city of Indianapolis constructed a flood control and water supply reservoir on Eagle Creek in the northwestern part of Marion County. Even before completion of that

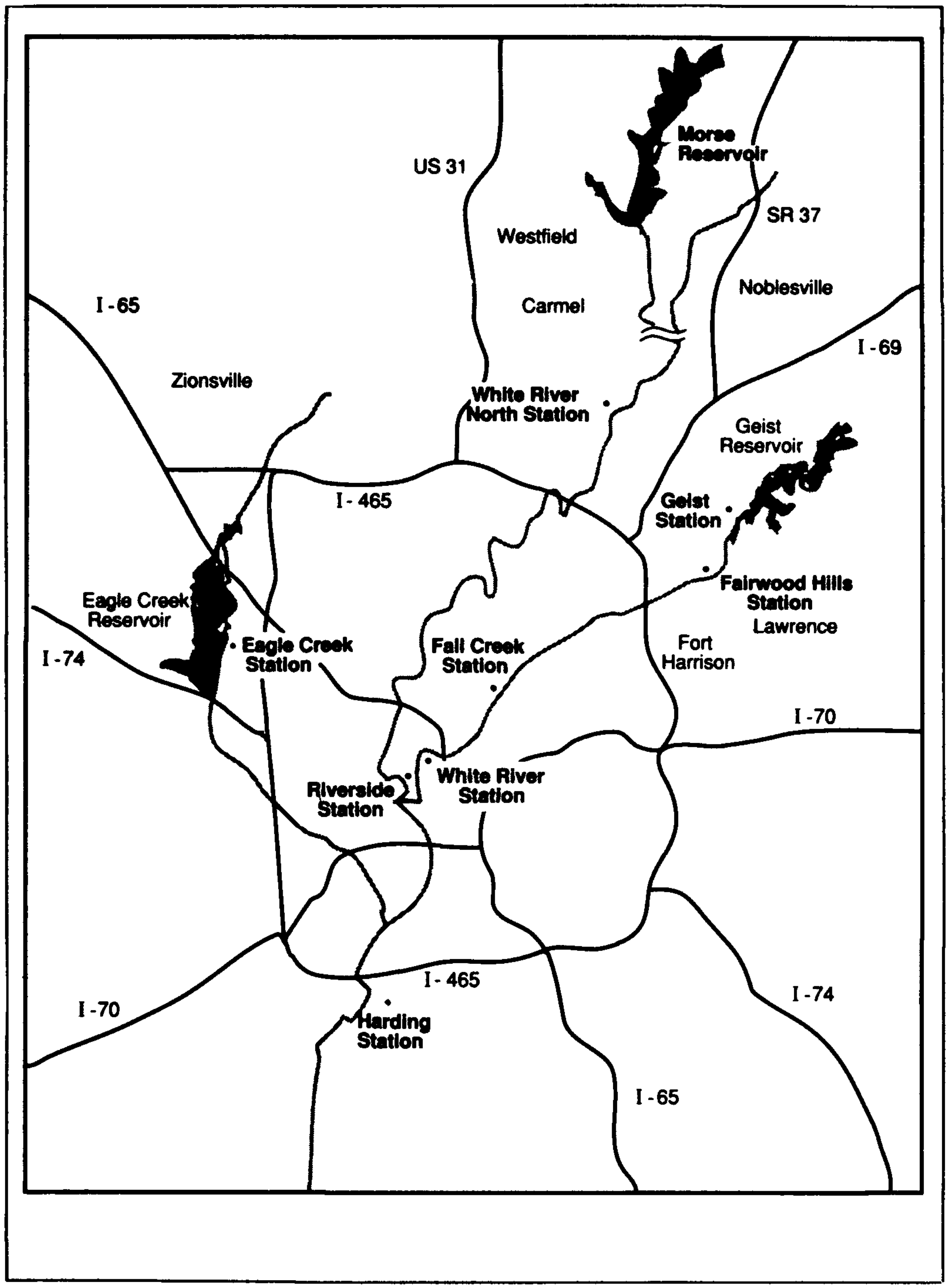

Figure 1. **Components of the Indianapolis, Indiana, water supply system.**

reservoir in 1968, the company began negotiations with city officials for a contract that would provide for a raw water supply from the city-owned reservoir. Since 1971, IWC has had a contract with the city that allows the utility to use an average of 12.4 mgd (47.0 X 10^6 L/day), with the first withdrawals of water beginning in 1976.

This set back the timetable for the completion of the proposed third company-owned reservoir until the late 1970s. In 1968, the company announced its plans to proceed with design and construction of the reservoir and immediately met with considerable negative reaction from residents and others in the affected area. The proposal for a third single-purpose water supply reservoir was eventually set aside in 1970 in favor of a second city-owned flood control and water supply project to be located in the same area, which in turn was shelved in favor of a proposed joint Corps of Engineers-State of Indiana-local project known as Highland Reservoir. This proposal was authorized by the Indiana General Assembly but never authorized or funded for advanced planning by Congress.

EXISTING WATER RESOURCES MANAGEMENT SYSTEM

Today, the three reservoirs constitute the major surface-water storage facilities used by the company to meet the bulk of the Indianapolis metropolitan area's water supply needs (Bakken, 1983). For water management purposes, Morse Reservoir and White River act as a single system. The base flow in the White River is normally adequate to satisfy the water supply needs of the White River Treatment Plant. During prolonged dry periods, releases from Morse Reservoir are used to make up deficiencies in natural White River flows. Water from the White River is diverted to the IWC canal at a pool created by the Broad Ripple Dam. This canal carries raw water from White River to the White River Treatment Plant, with essentially all of the flow in the canal being used at the treatment plant.

Although the base flow in Fall Creek is considerably less than the White River, the Geist Reservoir - Fall Creek source also acts as a single water management system. The deficiencies in Fall Creek flows are made up by releases from Geist Reservoir. Water is diverted from a pool behind a low-head dam and pumped a short distance to the Fall Creek Treatment Plant.

The third source of surface water is Eagle Creek Reservoir, located in the northwest part of Marion County and owned by the city of Indianapolis. Water is removed from the reservoir through an intake structure and pumped to the Eagle Creek Treatment Plant, located just east of the reservoir on 56th Street.

In addition, groundwater supplied by wells at four locations around the service area presently provides approximately 5 percent of the system's supply, and it is expected that groundwater will become increasingly important as system demands increase. Following the drought experienced in Indiana in 1988, IWC added two new 4 mgd (15.6 X 10^6 L/day) groundwater treatment plants and has put on line a new 12 mgd (45.4 X 10^6 L/day) surface-water treatment plant, the latter using the previously unknown added yield.

HYDROLOGIC STUDIES

Upon reflection, several unrelated events in the mid-1970s led IWC to initiate a study of reservoir system reliability. Foremost, the final demise of the proposed Highland Reservoir made it evident that the water utility would be dependent on all possible yields from its existing sources, and would need to find and develop groundwater supplies to meet anticipated water needs. IWC needed both to study its existing surface sources and explore new groundwater supplies if it wanted to assure adequate water for future community growth.

Fortunately, new reservoir engineering analysis technology began to appear in water-resources-related technical and research publications at a time when the company recognized existing reservoir dependable yield data to be missing, old, or inconsistent for each source. New technology included sonar surveys by boat to obtain reservoir bottom depths, improved surveying instruments, and computer hydrology programs for probabilistic drought studies.

In addition, data from new state and federal reports on area groundwater conditions suggested that substantial amounts of this resource could potentially be developed and used to meet future water needs of the Indianapolis metropolitan area.

RESERVOIR VOLUME SURVEYS

In 1977, IWC engineers began discussions with local engineering and surveying consultants to evaluate their experience and expertise in conducting depth sounding and shoreline survey studies that would assist in determining reservoir sedimentation and its impact on remaining storage volume. Schneider Engineering Corporation of Indianapolis was selected on the basis of experience, availability, and expected performance.

The field work for 25 cross-sections began in April 1978 and was completed in August of that year. The consultant's field data and report were received by IWC in September, and IWC's Engineering Department drafted the profiles and new bottom contours. Schneider Engineering performed the volume calculations, finding the 1978 volume to be 7.2 billion gallons (27.2×10^9 L) after 21 years, or 0.3 billion gallons (1.14×10^9 L) more than the reservoir design consultant's estimated original volume of 6.9 billion gallons (26.1×10^9 L). The 1978 volume survey clearly indicated that the original volume calculations had been in error, largely because of inaccuracies in determining topographic contours. Recomputation of the original volume suggested that Morse Reservoir had originally stored approximately 8.27 billion gallons (31.34×10^9 L) of water. Therefore, over the 21 years of its life, the reservoir had lost 1.07 billion gallons (4.05×10^9 L) to sedimentation, or 12.9 percent of the reservoir's estimated original volume.

Schneider Engineering also conducted the Geist Reservoir volume survey and began work on that project in February 1980. The field work, consisting of 40 cross-sections, was completed by May and the consultant's field data and report were received by IWC in June. The company's Engineering Department again drew the profiles and bottom contours, with the consultant performing volume calculations. The 1980 volume was 6.1 billion gallons (23.1×10^9 L), an 11.6 percent reduction from the 1943 computed volume of 6.9 billion gallons (26.1×10^9 L). The total cost for the volume determinations of both reservoirs, not including work completed by company personnel, was about $89,000.

DEPENDABLE YIELD CALCULATIONS AND DROUGHT STUDIES

Previous evaluation of the capabilities of the IWC's raw water supply system have focused on the 1940-1941 drought. Although the most severe historical drought is a valid benchmark for water supply planning, it is also useful to derive probabilistic estimates of reservoir yields or minimum streamflows. A study (Black & Veatch, 1985) was begun in 1984 by IWC's consultant, Black & Veatch of Kansas City, to (1) refine estimates of dependable yields for the components of the raw water supply system; (2) calculate probabilistic drought yields for each of the individual components of the system; (3) estimate both historical and probabilistic dependable yields for the entire raw water supply system with coordinated reservoir operation; and (4) develop a plan to manage the system of reservoirs to maximize combined dependable yield.

Engineering studies conducted prior to this study made no attempt to assign a probability to the yield estimate. These earlier studies estimated the total net dependable yield, based on the 1940-1941 drought, to be 112.4 mgd (425.9×10^6 L/day) (see Table 1). The first item addressed in the recent study (Black & Veatch, 1985) was a reassessment of the dependable yield estimates based on the 1940-1941 drought. New estimates were based on a recurrence of the hydrologic conditions that created this historical drought with reservoir storage volumes and additional upstream depletions as projected for the year 2000. Projections of storage reduction due to additional sediment inflows were facilitated by the reservoir volume surveys previously described and watershed studies completed by the Soil Conservation Service.

Major obstacles encountered in the analysis included (1) accurately evaluating the effects of upstream water users, particularly the cities of Muncie and Anderson, on drought flows in the White River; (2) estimating streamflows for ungauged areas tributary to the water supply reservoirs; and (3) accurately assessing system losses due to a variety of operational factors that reduce the actual amount of water available. Total losses, including those calculated for increased upstream water uses, were estimated to be 16.7 mgd (63.3 X 10^6 L/day) for the Morse

Reservoir - White River source of supply, 9.2 mgd (34.9 X 10^6 L/day) for the Geist Reservoir - Fall Creek source, and 5.6 mgd (21.2 X 10^6 L/day) for Eagle Creek Reservoir.

Based on the 1940-1941 drought flows, storage volumes available for gravity release under year 2000 conditions, and the system losses described above, the net historical dependable yields for the individual supply components were estimated by Black & Veatch in the recent study to total 127.0 mgd (481.4 X 10^6 L/day) (see Table 1).

Additional water in storage would also be available to augment yields in both Geist and Eagle Creek reservoirs if pumping facilities were or could be installed to use this storage. The additional storage from a quarry adjacent to Geist Reservoir that may be inundated in the future could increase the yield during the historical drought for the Geist Reservoir - Fall Creek system from 27.2 mgd (103 X 10^6 L/day) to 31.0 mgd (117 X 10^6 L/day). In Eagle Creek Reservoir, additional storage may be available at elevations below the intake level of IWC's 56th Street intake structure. Use of this additional storage, if an existing contract could be renegotiated, could increase the historical dependable yield from 12.5 mgd (47.4 X 10^6 L/day) to 14.4 mgd (54.5 X 10^6 L/day).

Yields were also calculated on the basis of probabilistic estimates of surface-water flows during droughts. Calculations were completed for estimates of the 10-, 20-, 50-, and 100-year droughts. Only estimates for a 50-year drought are presented here because this probability level was judged to be most appropriate for public water supply planning in central Indiana.

Table 1

Water Supply Dependable Yield Estimates, Indianapolis Water Company System

	Morse Reservoir-White River		Geist Reservoir-Fall Creek		Eagle Creek Reservoir		Total	
Type of Estimate	mgd	10^6 L/d	mgd	10^6 L/d	mgd	10^6 L/d	mgd	10^6 L/d
Previous yield estimates 1940-41 drought, gravity release	75.0	284.1	25.0	94.8	12.4	47.0	112.4	425.9
Revised yield estimates (1985) Historical flows, year 2000 conditions, gravity release	87.3	331.0	27.2	103.0	12.5	47.4	127.0	481.4
Historical flows, year 2000 conditions, pumped storage and gravity release	87.3	331.0	31.0	117.0	14.4	54.5	132.7	502.5
Statistical 50-year flows, year 2000 conditions, gravity release	87.6	332.0	26.8	102.0	12.4	47.0	126.8	481.0
System yield with coordinated operation								
Historical flows							134.6	510.0
Statistical 50-year flows							139.4	528.0

Based on these statistical determinations of minimum streamflows, year 2000 conditions for reservoir storage volumes, and system losses, the calculated 50-year net dependable yield of all sources was found to total 126.8 mgd (481 X 10^6 L/day), as shown in Table 1.

In all of the foregoing yield determinations, based on both historical and probabilistic droughts, values were calculated for the individual sources, but no mention was made of the yield of the system as a whole. Studies in other parts of the United States have demonstrated that severe droughts do not affect multiple watersheds as severely as single watersheds, and that the yield of a system of supplies for a given drought is greater than the sum of its parts. The case of the Indianapolis Water Company proved to be no different. A computer program was developed to coordinate withdrawals from the three reservoirs available for use by IWC to optimize system yield. Withdrawals were allocated among the reservoirs on the basis of the amounts of yield remaining in each as the drought progressed.

This ensured that those reservoirs having the greatest yield augmentation capability at any time were the ones stressed the most heavily. The benefits of coordinated reservoir operation are apparent if the "without coordination" system dependable yield values are compared to the "with coordination" values. As Table 1 indicates, IWC was able to increase its raw water supply capabilities from the original estimated 112.4 mgd (426 X 10^6 L/day) to an initial 126.8 mgd (481 X 10^6 L/day) with the addition of a new treatment plant, and could eventually expand to 139.4 mgd (528 X 10^6 L/day) by making more efficient use of the storage it already owns and operates. The economic benefits of the extra supply are substantial. The cost of the dependable yield study conducted by Black & Veatch was $85,000, while it is estimated that constructing a new IWC-owned water supply impoundment would result in a cost of at least $1 million for each 1 mgd (3.79 X 10^6 L/day) of dependable yield. As a result of the Black & Veatch study, IWC was able to construct a new water treatment facility that will use the additional 12 mgd (45.5 X 10^6 L/day) found to be available from the Morse Reservoir - White River source. The utility put its new White River North Treatment Plant and Pumping Station, located north of Indianapolis, on line in March 1991.

Another interesting aspect of the Black & Veatch study was an attempt to define the probability of the 1940-1941 drought, and thus to provide a basis for comparing dependable yield estimates for the historical drought and for probabilistic droughts. This was done first by using the probabilistic yield for each source of supply to develop a plot of yield versus probability. The values of the historical drought yields were then used with the yield probability curves to estimate the probability of the historical drought. On this basis, it was estimated that the historical drought had a return period of somewhere between 29 and 45 years. Return periods associated with individual sources were 45 years for Morse Reservoir - White River, 43 years for Geist Reservoir - Fall Creek, and 29 years for Eagle Creek Reservoir.

This comparison has great significance because the Indianapolis Water Company has based its water supply planning efforts on historical data from the 1940-1941 drought. As a check on these return periods, 113 years of precipitation data were analyzed. This analysis indicated that the 1940-1941 drought was the most severe in more than 100 years, which differs from the evaluation of drought probabilities based on statistical estimates of system yields. A review of both approaches indicates that there is considerable latitude in attempting to define probabilities associated with natural events, and the return period of the most severe event is strongly influenced by the length of record available for analysis. At this point, the conclusion must be that the most severe historical drought experienced in the Indianapolis area (1940-1941) has a return period of approximately 100 years.

CORPORATE COMMITMENT TO FUTURE PLANNING

The Indianapolis Water Company has had a long tradition of looking well into the future as it plans for water supply system improvements and, after experiences gained during the 1988 drought, the company has redoubled its efforts related to long-term planning. The components of the existing IWC planning activities include (1) estimation of future water supply needs, (2) developing a conjunctive-use approach to managing multiple and geographically diverse sources of supply, and (3) preparation of a comprehensive water shortage plan.

ESTIMATING FUTURE WATER SUPPLY NEEDS

The company's Planning Section, located within IWC's Engineering Department, is responsible for ongoing evaluation of both short- and long-range water supply and plant facility needs of the system. In 1988, several areas of the IWC distribution experienced reduced water pressure, largely brought on by lawn irrigation demand during already-high-demand periods. The challenge faced by our planning activities is to understand the year-to-year growth in our average daily usage and to also estimate peak-demand trends and the associated impact on distribution of water throughout the system. Since 1988, $50 million in capital improvements have been made to the IWC system as a result of recommendations developed via our planning efforts.

CONJUNCTIVE USE OF SURFACE AND GROUNDWATER RESOURCES

As Table 1 shows, coordinated operation of the three reservoirs results in an increase in surface-water supply capabilities from 112.4 mgd (426 X 10^6 L/day) to 139.4 mgd (528 X 10^6 L/day). This gain is made possible because of detailed management of these sources as a drought proceeds. In 1991, parts of the urban area have experienced extremely dry conditions while other areas are only slightly below average. Eagle Creek Reservoir is presently some 9 feet (2.44 M) below normal pool while Geist and Morse reservoirs are approximately 2 feet (0.61 M) below normal pool.

In addition to the coordinated management of reservoir sources, IWC will also be managing its groundwater withdrawals to maximize the "banking" of this water for times of greatest demand or in later portions of significant drought events. Groundwater development projects, with an anticipated composite production capability of approximately 80 mgd (303.2 X 10^6 L/day), will be constructed over the next 40 years as water usage increases. One problem already anticipated is the substantial difference in dependable yield methodology between groundwater and surface-water professionals, making the job of conjunctive management of these resources complex.

EMERGENCY WATER MANAGEMENT PLAN

IWC has recently begun to develop a comprehensive document that will provide guidance for responding to various types of water supply interruptions. This effort, still under way, includes personnel from the company's Distribution, Pumping, Customer Service and Engineering departments. The draft plan includes three stages of water emergency: (1) Water Watch, (2) Water Alert, and (3) Water Crisis, with each having attendant triggering criteria and recommended levels of response.

This plan was originally labeled a "drought plan," but it quickly became apparent that many other events, either man-made or Acts of God, can cause major water supply impacts and can trigger a need for a well-thought-out water management response.

CONCLUSIONS

Climate change and drought are two major elements in the long-range development and management of public water supply systems. The water needs of our society, particularly in the humid Midwest, oftentimes are greatest when supplies are at a minimum, thus leading to the potential for water resources shortages or conflicts.

The Indianapolis Water Company has found that, through a combination of studying regional water resources and water-demand trends, it can effectively meet the anticipated growth in the Indianapolis metropolitan area well into the next century. Recently completed studies of the IWC supply sources have shown that coordinated management of reservoirs can increase dependable yield of those sources significantly. That work, coupled with

ongoing groundwater development projects, conjunctive use of sources, and preparation of an emergency water management plan, will allow IWC to respond to changing customer water demands and fluctuations in climate conditions.

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PROPERTY RIGHTS AND GROUNDWATER DEVELOPMENT IN A CHANGING CLIMATE: A CASE STUDY

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ABSTRACT

Where water becomes scarcer as a consequence of global warming, there may be increased pressure to develop new sources of supply, including increased extraction of groundwater. The case examined here suggests that this adjustment strategy may generate costly disputes, as other water users, communities, and environmental interests seek to protect the values that they currently derive from that resource.

A transaction cost theory of property rights is applied to analyze the nature of these conflicts. It is found that the measurement and enforcement of property rights to groundwater are difficult, given the nature of the resource and the effects of climate variability and human activities. This has affected the evolution and functioning of institutions governing groundwater use, and will likely affect the cost of securing rights to develop new groundwater projects.

The analysis is applied to a case study of a current conflict between a private water development company and the citizens and water users of Colorado's San Luis Valley. The potential for institutional adjustments to the impacts of climate change on water availability is then addressed, and policy recommendations are presented.

INTRODUCTION

Increasing atmospheric concentrations of carbon dioxide and other radiatively active trace gases may lead to global warming over the coming decades, with potentially large, but very uncertain, impacts on water resource availability (Smith and Tirpak, 1989; IPCC, 1990; Waggoner, 1990; Lins et al., 1991).

Climate models suggest that global warming may result in large changes in the regional and seasonal distribution of precipitation and runoff, with possible reductions in summer soil moisture and runoff in mid-latitude, mid-continental regions such as the central portion of the United States (Manabe and Wetherald, 1986; Kellogg and Zhao, 1988). However, the uncertainties in these models and their coarse resolutions make them incapable of yielding reliable forecasts of changes in regional water availability (IPCC, 1990; Schneider et al., 1990).
Hydrologic model simulations suggest that for many river basins even small changes in temperatures and precipitation can have very large impacts on the amount and seasonal timing of available runoff (Revelle and

Waggoner, 1983; Gleick, 1987; Schaake, 1990). A result with particular significance for the western United States is that increased temperatures (assuming no changes in seasonal precipitation amounts) might substantially increase winter runoff and reduce summer runoff in river systems fed by mountain snowpacks. This suggests that increased scarcity of water during the summer, when competing agricultural and urban water demands are at their peaks, is a real possibility, although by no means a certainty.

Human responses to actual or feared changes in water availability will be as important as the physical changes themselves in determining their ultimate socioeconomic effects. In areas where surface-water availability or reliability diminishes as climate change occurs, there are likely to be increased efforts to develop new sources of supply. These may include increased storage capacity for surface water as well as increased use of groundwater resources. It would be a mistake, however, to conclude that it will be a simple matter to implement these obvious response strategies, or that the problems encountered will be primarily technical in nature.

Rather, the recent history of water conflicts in the arid and semi-arid western United States suggests that decisions regarding the development of major new water projects can no longer be made unilaterally. Where water is scarce relative to the multiple demands on the resource, interdependencies among competing users have often become a source of conflict when changes in use or management are proposed. As the water resources of the western states have become more fully used and as the value of instream uses has increased with growing population, growing demand for recreational opportunities, and increased environmental awareness, proposals for new water projects have come under more intense scrutiny and criticism. This has affected both major public projects such as Denver's proposed Two Forks Dam (Rhodes et al., in press) and private ventures as well, as shown by the case study presented here.

The case in question is an attempt by a private company, American Water Development Incorporated (AWDI), to establish the right to drill wells into the aquifer system underlying southern Colorado's San Luis Valley (Figure 1) for the purpose of annually extracting up to 200,000 acre-feet (246.6×10^6 m^3) of water. The company is proposing to export much of this water from the valley by building a pipeline over Poncha Pass, at the north end of the valley. The water would then be available for sale to Denver and other Colorado cities along the eastern slope of the Rocky Mountains.

This proposal has been vehemently opposed by the majority of San Luis Valley residents as well as by state and federal agencies and environmental interest groups. The company and its opponents are scheduled to begin presenting their cases before the Division 3 Water Court in Alamosa this month (October 1991), and the case promises to be one of the most expensive in Colorado's history. Why has this proposed project generated such costly contention? Existing users of the valley's water resources and the other objectors in the case apparently feel that their own interests will be seriously damaged if the project is allowed to proceed. To what extent does this perceived vulnerability arise from the nature of the groundwater resource and from the nature of property rights to the resource, and to what extent does it depend on the identity of the players?

The following section discusses the problem of defining and enforcing property rights to groundwater. The sources and evolution of the conflict in the San Luis Valley are then examined. A concluding section addresses policy steps that can be taken in anticipation of the possible effects of future climate change in order to reduce the costliness of such conflicts in the future and to increase the efficiency and equitability of future water allocation.

GROUNDWATER RIGHTS

Groundwater has presented especially difficult problems in creating rules for its allocation and use. The difficulties have arisen both from the invisible nature of the resource and from the inevitable linkages among groundwater users. Tarlock (1985, p. 699) has provided this analysis:

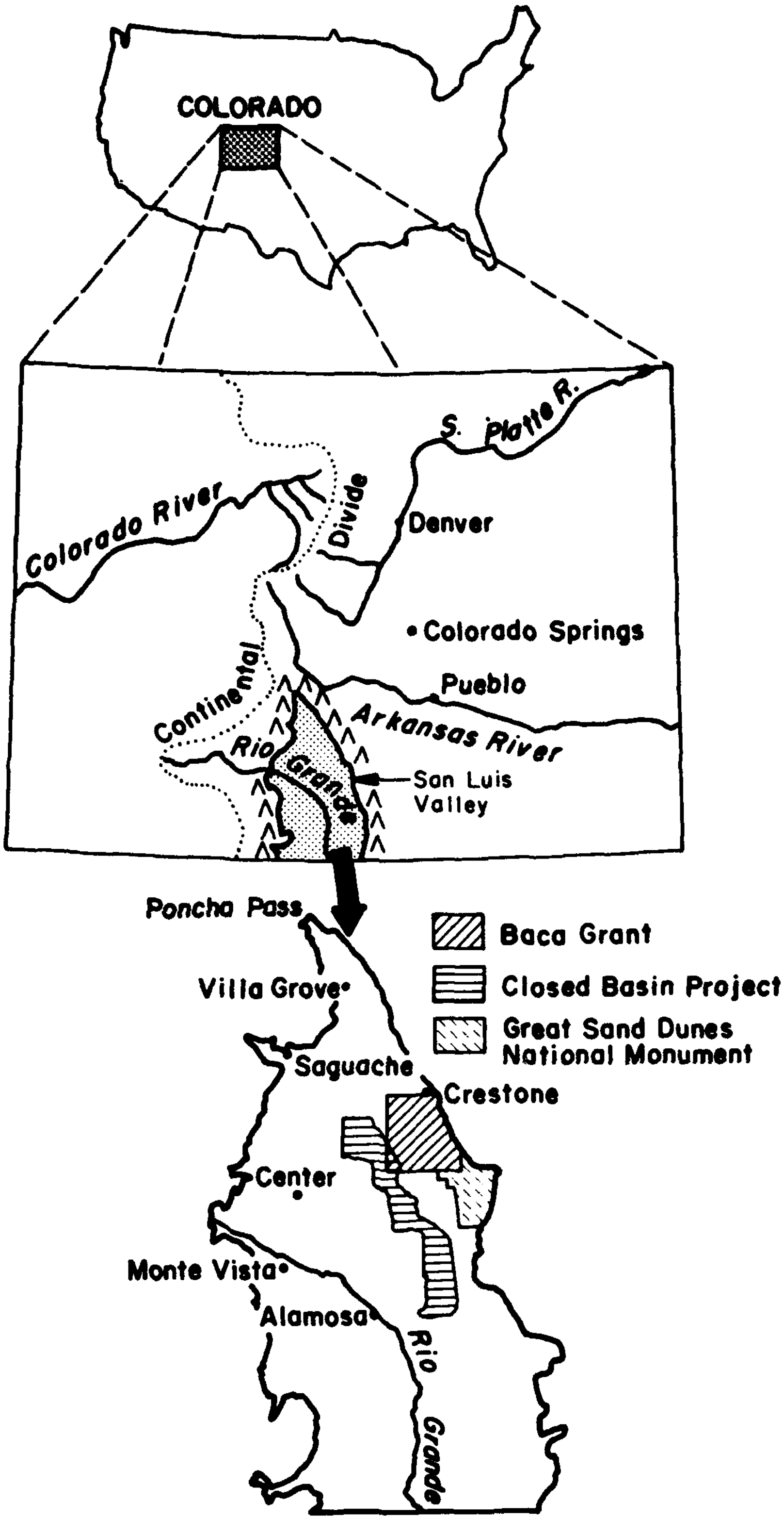

Figure 1. State of Colorado and detail of central region.

Source: S.L. Rhodes, K.A. Miller, and L.J. MacDonnell, "Institutional Response to Climate Change: Water Provider Organizations in the Denver Metropolitan Region," *Water Resources Research*, in press, 1991, copyright by the American Geophysical Union.

> It is difficult to assign exclusive rights to a resource when, for physical reasons, one claimant's consumption inevitably interferes with another's legitimate consumption. A groundwater basin is not like a coal reserve which can be divided among different landowners; groundwater must be shared at all times by a large number of users. One pumper's use affects both the quantity and pressure rates available to other pumpers.

In the early 1800s, when groundwater hydrology was viewed as a nearly unfathomable mystery, English courts established the "absolute ownership" principle by which ownership of land provided a nominally absolute right to the development of any groundwater underlying that land. The lack of any limits on use of the resource merely avoided the issue of liability for damages to other groundwater users.

As conflicts over the consequences of the absolute ownership rule became more frequent, many American courts moved toward a "reasonable use" standard. According to that standard each overlying landowner is allowed to make reasonable use of the resource in view of the similar rights of others. However, as long as the water is used on the overlying land in a manner deemed by the courts to be reasonable and beneficial, there is essentially no limitation on the quantity of water withdrawn, and water may be drained from underneath adjacent land without liability. Most eastern states have adopted this general rule, as have the western states of Arizona, Nebraska, and Oklahoma (Aiken, 1980).

Another approach based on overlying land ownership is the "correlative rights" doctrine developed by the California courts: "All pumpers have rights of equal dignity. There is no temporal priority among overlying pumpers, and overlying owners do not have a right to the maintenance of the natural water table" (Tarlock, 1989, at 4-16). However, if an aquifer is being depleted, overlying owners may be required to reduce their use on a coequal basis (Anderson et al., 1983). If water is available that is considered "surplus" to the needs of the overlying landowners, it may be transported for use on nonoverlying lands.

Most western states apply the basic principles of prior appropriation in allocating groundwater. Rights are acquired by use under a permit granted by the state authority, after it is determined that unappropriated water is available and no injury to other water users will result. The permit application specifies the quantity of water to be withdrawn (and/or the maximum rate of withdrawal), the well location, the purpose of use, and the place of use. As with surface water, seniority of the right establishes priority to withdraw water in event of shortage. However, demonstrated well-to-well interference is usually required for the enforcement of groundwater priorities and only Utah follows a rule of protecting senior groundwater rights by allowing no net aquifer depletions. Appropriation rights appear to be better defined than other types of groundwater rights but they, too, leave open the question of sorting out responsibility for the effects of pumping on the rights of others.

Inability to adequately manage groundwater pumping under general rules has led many states to authorize the use of special management areas in which special rules are established. Depending on the state, groundwater development in these areas may be subject to permit requirements, well spacing requirements, well construction standards, allocation preferences, limited pumping rates, restriction on place of use, water use monitoring and reporting, and other similar requirements.

Another factor complicating the delineation of rights to groundwater are the hydrologic connections between groundwater and surface water. While water law has historically treated surface and sub-surface water separately, courts often have treated groundwater that is closely and demonstrably connected to a surface stream as part of the same system (Tarlock, 1989; MacDonnell, 1990).

Colorado has integrated the rights to surface water and tributary groundwater by statute. (Act of May 3, 1965, 1965 Colo. Sess. Laws, ch. 318, 1; Colo. Rev. Stat. 37-92-101 to 37-97-602 (1973 & Supp. 1987).) The state employs a broad definition of groundwater that is to be considered tributary to surface sources, in that groundwater can be deemed nontributary only if its use will not affect the rate or direction of movement of water in a natural stream within 100 years. Under Colorado law, the use of tributary groundwater is subject to administration in conformity with the priority system. However, since there is often a considerable time lag between the use of groundwater and its effect on a surface stream, the law directs the State Engineer to restrict well pumping only in circumstances where actual injury to senior surface rights will be thereby avoided.

A Theoretical Perspective

Recent economic analyses of the nature of property rights suggest that fully exclusive private property rights are much rarer than is commonly supposed. Barzel, for example, argues that it is important to recognize that property rights are not absolute and are not determined only by law, since

> The rights people have over assets (including themselves and other people) are not constant; they are a function of their own direct efforts at protection, of other people's capture attempts and of government protection.... rights are never complete, because people will never find it worthwhile to gain the entire potential of "their" assets (Barzel, 1989, p. 2).

The attributes of an asset that are not effectively defended as private property are said to lie in the public domain, and their value is vulnerable to capture by parties other than the nominal owner.

From this theoretical perspective, property rights can be seen as molded by transaction costs, where these are defined as the costs of capturing, enforcing, and transferring property rights. Where measurement is costly and where the value that an individual can derive from an asset is affected both by natural variability and by the actions of other individuals, the enforcement of exclusive individual rights becomes especially difficult. In such circumstances, competing efforts to capture the potential value of a resource may tend to result in the dissipation of that value.

The creation of rules of access and enforcement mechanisms can reduce this competitive dissipation of value. A question of central interest to property rights theorists is as follows: Under what circumstances will self-interested individuals cooperate to create such rules and mechanisms? This transaction cost approach suggests that as the potential value of a resource increases, there will be increased efforts to capture the value of aspects of the resource to which property rights are not already clearly defined and enforced. Where these efforts will lead depends upon how costly it is to organize to alter rules of access and to enforce them, and whether or not any party has a comparative advantage in exerting control over the resource. If such an advantage exists, its possessor may become the effective owner of the resource. Otherwise, increased dissipation of value can be expected where the cost of organizing is prohibitive, and more carefully delineated rules of access can be expected where cooperation is not prohibitively costly. A change in circumstances, such as a change in political system or an improvement in measurement technology, can change the relative likelihood of these alternative outcomes.

Groundwater resources fit the description of a resource for which it is difficult to define and enforce individual rights. The amount of water available and the pressure head fluctuate with both naturally varying conditions and with use, and it is often costly to measure the relative size of these effects.

The evolution of groundwater law, as previously described, can be seen as a process of managing the competition that has resulted from the increasing potential value of the resource. The evolving controversy over the proposal by AWDI to establish a new groundwater right in the San Luis Valley can be seen as a step in this process.

AWDI AND THE SAN LUIS VALLEY

In 1986, AWDI filed its plan to drill wells into a deep aquifer underlying the company's extensive landholdings in the San Luis Valley of southern Colorado, and to export water to cities along the dry eastern slope of Colorado's Rocky Mountains (the Colorado Front Range). These plans were encouraged by expectations that the urban water agencies would be willing to purchase this water at a price that would make the project a profitable venture. (The Metropolitan Denver Water Authority has recently indicated its willingness to pay up to $6,000 per acre-foot for reliable new supplies delivered into the Denver system. The capital value of a reliable water right for agricultural use within the San Luis Valley appears to be less than $500 per acre-foot (Foster, 1990c).) Forecasts of rapid population growth in the Denver metropolitan area and in other Front Range cities, and increasing environmental constraints on the development of new surface-water reservoirs, undoubtedly enhanced the investors' profit expectations. AWDI based its application for the necessary water rights on hydrologic studies suggesting that the deep aquifer contains an enormous volume of water that has scarcely been tapped by present groundwater users.

The aquifer system in the San Luis Valley is multi-layered (see Figure 2). A shallow "unconfined" aquifer receives substantial recharge from surface streams and from seepage from the valley's surface-water irrigation system. This aquifer has also been heavily tapped for irrigation, particularly on the western side of the valley, where its level appears to be closely connected to the flow of the Rio Grande. A thick layer of blue clay separates the unconfined aquifer from a deeper "confined" aquifer, which consists of several layers, each at least partially separated from the others by confining beds (Hearne and Dewey, 1988). There are numerous small domestic and stock-water wells and some large-capacity irrigation wells in the confined aquifer, many of which are under sufficient artesian pressure to flow to the surface. There are hydrologic connections between the shallow and deep aquifers, although the extent of these connections is subject to dispute.

In addition to the vertical stratification, only part of this aquifer system is considered to be hydrologically connected to the Rio Grande River. Near Crestone, there is an area referred to as the "Closed Basin" where surface streams and the unconfined aquifer are internally drained by evapotranspiration from crops, natural vegetation, and soil and water surfaces. AWDI has proposed to drill its wells into the deep aquifer in the Closed Basin area.

When AWDI submitted its application for the necessary well permits to the State Engineer's office, the application was rejected. The State Engineer considers the confined aquifer to be hydrologically connected to the Rio Grande River. Because the state has had difficulty meeting its commitments under the Rio Grande Compact, no permits have been issued for new large-capacity wells in the confined aquifer for many years. (The compact governs the allocation of water from the Rio Grande River among Colorado, New Mexico, Texas, and Mexico.) The state also argues that any further pumping would adversely affect natural wetlands and the water rights of other well owners.

AWDI filed suit in the Division 3 Water Court in Alamosa to have the State Engineer's decision overturned The company argues that its own hydrologic models as well as research performed by the U.S. Geological Survey suggest that the impacts of its project on Rio Grande flows and other water users would be minimal and could be mitigated easily. AWDI argues that the primary effect of its project will be to reduce the evapotranspiration of water by natural vegetation. Since this is argued to be a nonbeneficial use under Colorado law, and since "approximately 1.9 million acre-feet of water is lost each year in the valley due to nonbeneficial evapotranspiration" (AWDI, 1991, p. 2), the company argues that there is a substantial quantity of unappropriated water available for development. In fact, both AWDI's proposed Baca project and the U.S. Bureau of Reclamation's nearby Closed Basin project have been based on making use of this unclaimed water. (The Closed Basin project is under construction and has begun partial operation. It is intended to pump as much as 117,000 acre-feet annually into the Rio Grande River to assist Colorado in meeting its Rio Grande Compact obligations to New Mexico, Texas, and Mexico.)

AWDI further argues that its proposed compensation and augmentation plan would fully mitigate any adverse effects of its project. However, this plan was not unveiled until the company submitted an amended application to the Water Court in August 1990, in apparent response to intense opposition to the proposed project. The amended application proposes to compensate other well owners for any increased pumping costs or any required deepening of their wells resulting from AWDI's pumping. It also proposes to implement the project in phases with

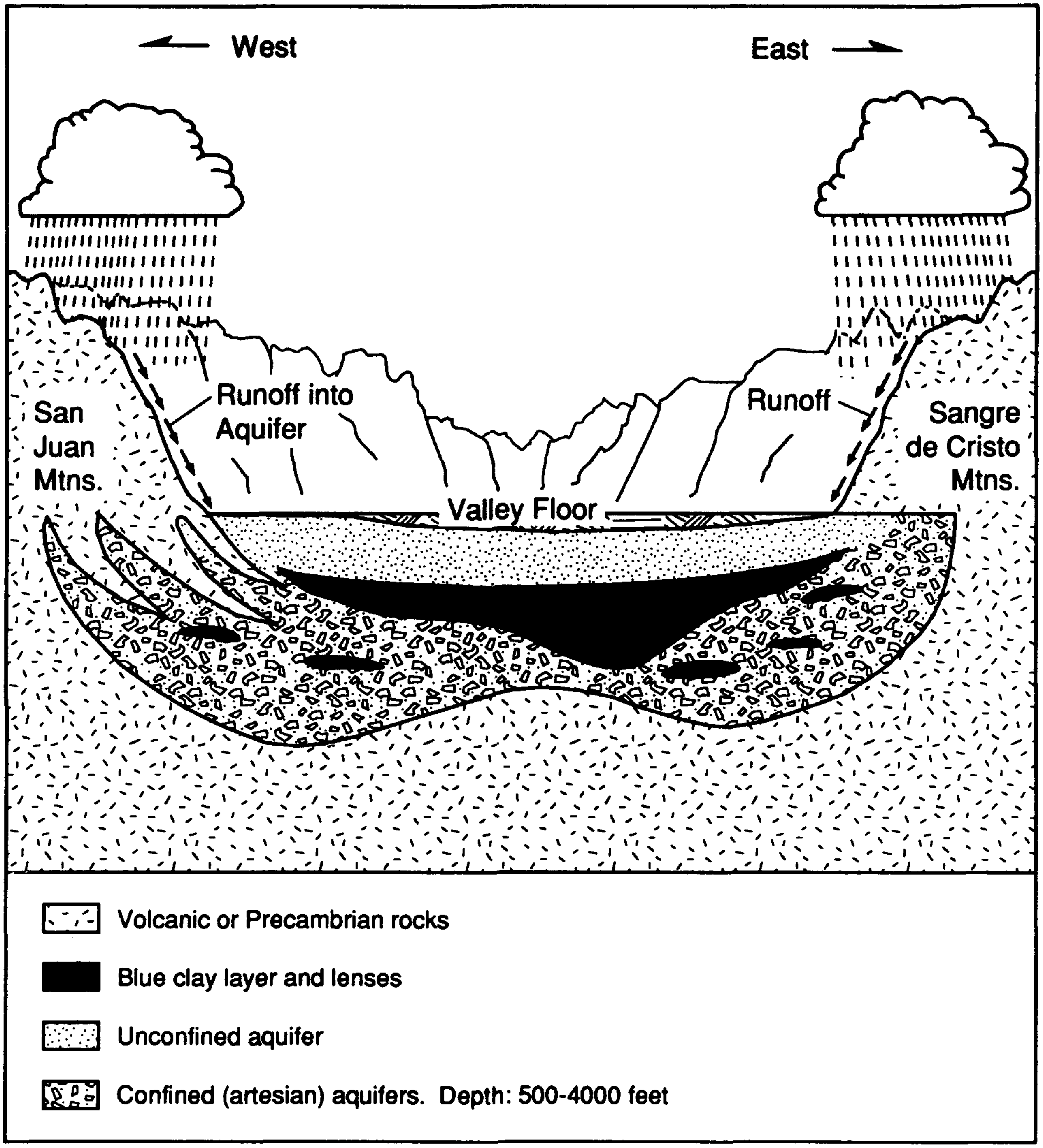

Figure 2. **Cross section of San Luis Valley.**

first-phase pumping of 60,000 acre-feet, primarily from the company's property near Villa Grove at the far north end of the valley. The company has promised not to proceed with second-phase development of the remainder of the originally proposed 200,000 acre-feet if the first phase is shown to adversely affect other wells (Foster, 1990a, b).

By the time that the amended application was submitted, a large number of water user organizations, environmental interests, and state and federal agencies had entered the suit as objectors. Under Colorado law, owners of water rights are required to take an active role in protecting their water rights against damage from prospective new projects and from the transfer of existing rights to a different place or type of use. The party proposing the change must present evidence to the Water Court that its actions will not damage other rights. If other water users feel that their rights may still suffer damage, it is their obligation to object to the application and present supporting evidence to the court.

Opposition to the AWDI proposal was elevated by the company's initial argument that Spanish, rather than Colorado, water law should apply in its case since the company's 100,000-acre Baca Ranch, on which most of the proposed wells would be located, was originally a Spanish land grant (AWDI, 1986). Under the terms of the 1848 Treaty of Guadalupe Hidalgo, the company would have had (nominally) absolute rights to use the water underlying its property, allowing it to proceed with pumping without regard for the effects on other water users. The Water Court quickly dismissed that argument in a preliminary hearing, but this maneuver was viewed by other water users as a naked attempt to capture part of the value of their own property rights.

Currently at issue in the AWDI case are fundamental differences of opinion about the nature of the valley's hydro-meteorology and about the system's ability to support water exports on the scale proposed by AWDI. Hydrologic modeling of the system is a relatively recent endeavor and much uncertainty remains about the nature of the confined aquifer system and its connections to the Rio Grande River, to the unconfined aquifer, and to surface-water bodies. There is also uncertainty and disagreement about the impact of the project on the valley's wetlands and about the role of the confined aquifer in maintaining the geological stability of the nearby Great Sand Dunes National Monument.

The fact that the hydrology of the system is complicated and poorly understood suggests that the cost of measuring the true impacts of AWDI's water withdrawals on natural ecosystems and on other water users will not be trivial. The measurement problem is further complicated by the natural variability of the system. Inter-annual variations in precipitation and in the use of surface water and groundwater in the valley cause fluctuations in the level of the water table in the unconfined aquifer as well as in the artesian pressure of the confined aquifer, although these changes are never uniform across the valley. After some lag, these fluctuations are assumed to affect the flow of the Rio Grande River as well.

Farmers in the valley argue that this variability will be the biggest impediment to implementation of AWDI's proposed compensation scheme. As Melvin Getz (1990), the Secretary-Treasurer of the Rio Grande Water Users Association, argues:

> ... if an artesian well, located on my ranch 50 miles from the project area, quits flowing five years after AWDI starts pumping the aquifer, is it due to their pumping or the drought? Who will decide? Will a computer model, whose output is varied by an operator's assumptions, make the decision?

Were it not for the difficulty of measuring impacts in the presence of natural variability, it would perhaps be no problem to establish a compensation package that would be acceptable to current owners of water rights. However, they are skeptical of AWDI's offer, since they have no guarantee that their claims for compensation will go unchallenged. It should be noted, however, that given costly measurement, it is also possible that they may be compensated even if they are not truly harmed.

Holders of vested water rights are not the only interests that can be damaged by the AWDI project. Local business owners and residents of the valley's small towns as well as several environmental groups are among the most vocal opponents to the project. The business owners and townspeople appear to believe that the movement of water out of the valley will lead to reduced agricultural activity and reduced tourism, causing their incomes to fall. The environmentalists fear damage to the valley's extensive wetlands and to the Great Sand Dunes National Monument.

The rights of these entities to the water resources involved are not clearly defined, which impairs their ability to bargain for compensation for damages arising from the project. The small-town interests, for example, have no recognized rights to the water now used for irrigation and the maintenance of natural habitats. However, their vocal opposition to AWDI's proposal can be seen as an attempt to exert a claim on a continued stream of benefits from the present use of the resource.

The opposition of irrigators, environmentalists, and small-town interests to AWDI's proposed project arises from the fact that they do not have completely secure rights to the water resources whose services they now enjoy, making the value of these services vulnerable to capture. This insecurity is evidenced by the fact that these parties are undertaking considerable expense to defend their interests against the possible impacts of the AWDI project.

AWDI has made some conciliatory offers in an attempt to garner the goodwill of valley residents. In addition to the terms of AWDI's amended application, the company has proposed to invest in a local development program that would keep part of the project's water and part of its increased economic value in the San Luis Valley (Foster, 1990c). The company is viewing this effort as an offer to share part of the gains from the project with the valley's residents. To the extent that it entails a sharing of the expected net social gains from their water development project, this offer would exceed the requirements of Colorado's "no injury" rule. The fact that AWDI should feel compelled to make such an offer suggests that the prospective gains from the project are also, to some extent, in the public domain, and therefore vulnerable to capture by other parties.

Although the company has found local residents willing to participate in its development program, this plan and the amendments to the company's application to the Water Court appear to have done little to quell mounting opposition to its project (Foster, 1990b, c). The fundamental mistrust of AWDI and its promises that is apparent among valley residents may be evidence of a problem that is likely to be encountered whenever the representatives of urban interests enter rural areas in search of additional water supplies. Personal trust and mutual interdependence within a cohesive community may lower the cost of enforcing individual rights to a shared resource. Where these elements are missing, costly disputes may be more likely.

The substantial costs being incurred in the ongoing legal battle over AWDI's proposed project represent a dissipation of the potential gains from this project. To some extent, such dissipation is inevitable, given the vulnerability of other users of the valley's water resources to the potential impacts of this project. This vulnerability has induced these parties to take actions to protect their own interests, and these actions have substantially increased the cost to AWDI of establishing the proposed new property right.

CONCLUSIONS

Where water becomes or is expected to become more scarce as a result of climate change, its potential marginal value will increase. Our analysis suggests that this can be expected to result in increased competition to establish property rights over water resources that now appear to lie in the public domain. In addition, since property rights are incomplete for water resources that are now "privately" owned, competition to capture their increasing value can also be expected.

The AWDI case illustrates the fact that proposals to establish new water rights or to move water to new uses can generate costly disputes even when there is a well-established legal and institutional framework for making such changes. We argue that the problem of determining the actual impacts of a water transfer in the presence of uncertain hydrology, compounded by natural variability, is often a source of costly disputes. In addition, when large exports of water are proposed from rural areas, local communities frequently oppose the change (Gould, 1988). They sometimes organize that opposition in an effort to exert their previously undefined rights to enjoy benefits derived from continued local use of the water.

To some extent, the problem lies in the nature of the resource and in the cost of defining the rights of all interested parties, rather than solely in laws that can be altered with the stroke of a pen. However, this is not a problem without solutions. In individual cases, the process of dispute resolution generates improved information on the hydrologic connections between the water rights involved, which tends to clarify the relative rights of the parties and may lower subsequent enforcement costs. On a broader scale, as the value of water has increased in the western states, increasing efforts have been undertaken to improve the quality of water rights records and to institute legal reforms designed to improve their transferability. This suggests that adjustments to the effects of climate change may result in a similar evolutionary process toward further clarification of the relative rights of competing water users.

The role of hydrologic uncertainties in water disputes suggests that increased public investment in hydro-climatologic data gathering and in the documentation of existing water uses is a public policy response that may be worthwhile to begin undertaking now, in anticipation of the impacts of global warming. In addition, greater attention can be given to the creation of appropriate means for resolving disputes over the effects of changes in water use on parties other than holders of vested water rights. The goal should be to prevent significant uncompensated adverse effects while ensuring that disputes over trivial effects do not lock water into low-valued uses or dissipate the potential gains from socially beneficial transfers and new uses.

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PLANNING FOR MUNICIPAL WATER SUPPLIES WITH A FUTURE CLIMATE CHANGE: THE TWO FORKS VETO AS AN ANALOGUE

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ABSTRACT

This study addresses regional adjustments to possible reductions in water availability that may accompany a future climate change. The study assesses potential responses of urban water suppliers to reduced water availability by examining an analogous case of reduced supply in the Denver metropolitan region.

In this case, the EPA's veto of the Two Forks Dam prompted water providers in metropolitan Denver to take action to ensure adequate future water supply. In some cases, actions taken since the veto process began represent a departure from previous water provider policies. It is argued that similar institutional adjustments may occur due to climate-change-induced reductions in regional water supplies, and that useful lessons may be drawn from an analysis of institutional responses to the Two Forks veto. This paper introduces what is envisioned as a long-term assessment of adjustments to reduced future water supplies in the Denver metropolitan region. (**Note**: This paper is adapted from S.L. Rhodes, K.A. Miller, and L.J. MacDonnell, "Institutional Response to Climate Change: Water Provider Organizations in the Denver Metropolitan Region," *Water Resources Research*, in press, 1991, copyright by the American Geophysical Union.)

INTRODUCTION

This paper addresses the issue of social and institutional capabilities at the regional level to cope with possible consequences of a global climate change. It focuses on an existing situation involving the loss of an expected large water supply source to a growing metropolitan area located in a semi-arid environment. The loss of an expected major water supply can be viewed as analogous to the possible reduction in water supply projected to occur in some North American regions as a consequence of global warming (Revelle and Waggoner, 1983; Kellogg and Zhao, 1988). Analysis of the institutional responses to this situation through the next several years may provide useful insights into societal capacity to cope with the regional effects of future climate change. The relevance of this case study arises from the likelihood that the impacts of global warming will be addressed within the framework of existing institutional relationships and legal/political constraints. Understanding how our water institutions respond to contemporary circumstances may provide some guidance for future water resources planning in a "greenhouse" world.

The paper introduces a "living laboratory" case study of institutional response to climate change using the "analogue" method: the behavior of Denver metropolitan area water providers following EPA's veto of the Two Forks Dam project. Legal and historical factors likely to affect responses to the Two Forks veto are identified and discussed in the context of understanding regional responses to possible impacts of climate change.

CLIMATE CHANGE AND WATER RESOURCES

Global warming could have profound impacts on regional water availability (Tegart et al., 1990). At present, the nature of those regional impacts cannot be reliably predicted. However, numerical climate models suggest that global warming may result in large changes in the regional and seasonal distribution of precipitation and runoff, with possible changes in regional runoff on the order of +/-50 percent (Schneider et al., 1990). Some climate model studies suggest that mid-continental regions such as the Great Plains of the United States may experience reduced summer soil moisture and decreased runoff over the course of the next century (Manabe and Wetherald, 1986; Mitchell et al., 1987; Kellogg and Zhao, 1988).

Hydrologic modeling of specific river basins also suggests the possible impacts of climate change on water resources in the western United States. For example, studies of the Sacramento River (Gleick, 1987) and the Animas River (Schaake, 1990) suggest that a 2°C increase in temperature, with no change in seasonal precipitation amounts, would significantly increase winter runoff and decrease summer runoff. In addition, Revelle and Waggoner (1983) have estimated that a 2°C warming would reduce the Colorado River's mean annual flow by 23 to 35 percent, corresponding roughly to the mean annual flow in the 1976-1978 period, one of the driest periods in that river basin since 1906 (Meko and Stockton, 1984).

In order to grasp fully the implications for important issues such as water supply and use, physically based models must be complemented with knowledge of the processes of socioeconomic adjustment to environmental change. An understanding of decision-making in response to environmental change is a necessary precursor to effective policy planning for global warming. Our goal is to identify ways to incorporate the human element in an analysis of the socioeconomic impacts of possible changes in future water availability and, ultimately, our policy options for addressing such changes.

We propose to approach the analysis of possible institutional responses to climate change through the use of an analogue. Rather than speculating about an uncertain future to assess societal responses to global warming, we propose to study how institutions in a particular regional setting respond to a situation analogous to that which might be associated with climate change (Glantz, 1988). Our reasoning is that in order to learn about how societal institutions may be able to cope with a possible climate change, we can study how they respond to similar future conditions created by other influences--in this case the loss of a large water storage reservoir intended to augment regional water supply well into the future.

Among the advantages of the analogue approach is the fact that analogous cases provide detail and realism not possible with hypothetical scenario construction or with numerical forecasting (Jamieson, 1988). The importance of such elements as timing, chance, innovation, and surprise may become apparent in an analogous case history. An analogue invites one to explore the possible similarities and differences between the case at hand and a possible future situation. In doing so, one is induced to investigate a variety of societal response alternatives to actual physical and socioeconomic changes and to assess why particular responses occurred.

THE CLIMATE-CHANGE ANALOGUE: THE TWO FORKS VETO

The Denver metropolitan region, largely through the efforts of the Denver Water Department (DWD), has met its growing water supply needs during this century by the periodic expansion of its surface-water diversion, storage, and delivery systems. The most recent addition to this infrastructure, the Two Forks project, was to be a new dam on the South Platte River 25 miles upstream from Denver. The reservoir would have a capacity of 1.1 million acre-feet (13.6 X 10^9 m^3) and a projected annual average yield of 98,000 acre-feet (1.2 X 10^8 m^3). Most of the water to be stored would come from the western slope of the Rocky Mountains through trans-mountain diversions. The project would be jointly built and operated by the DWD and a group of approximately 40 suburban local governments and special districts (the Metropolitan Water Providers).

The need for the Two Forks project was based on population growth forecasts for the metropolitan Denver region and related analyses showing a shortfall in water supply by the year 2010 (DRCOG, 1986). The final Two Forks environmental impact statement reported that the annual shortage would reach 166,000 acre-feet by 2035 (U.S. Army Corps of Engineers, 1988). The Corps of Engineers approved the Section 404 permit necessary to construct the project in 1989, but shortly thereafter EPA Administrator William K. Reilly announced his intention to veto the permit and, with it, the entire project. With the Two Forks option now seemingly unavailable, water providers in metropolitan Denver were confronted with the need to find alternative means of meeting an anticipated reduction in regional water supply. EPA's first veto decision came in late 1990.

We suggest that the loss of a future Two Forks water supply is analogous to what might result from a reduction in regional water supplies due to climate change for a number of reasons:

- Two Forks was expected to be the primary additional water supply for the metropolitan Denver region for the next 50 years. While the Two Forks project lost support because of concerns about future climate change, it was to provide water during the period in which the effects of global warming on water supply coincidentally are projected to become evident (Houghton et al., 1990).

- The Two Forks project is based on capturing surface-water flows derived primarily from snowmelt in the Rocky Mountains on both sides of the Continental Divide. The unavailability of this storage may be analogous to the consequences of a future reduction in snowfall and other precipitation in this particular area of water supply collection.

- The absence of Two Forks Dam (or even a reduction in its storage capacity) decreases the ability to control the timing of water availability for municipal use and to satisfy the rights of downstream senior users. This is analogous to possible seasonal changes due to global warming, wherein available water would flow downstream during the low-demand winter season rather than during the high-demand summer season.

- Loss of the assumed Two Forks supply affects most of the water providers that serve a majority of the population in the Denver metropolitan region, as would be the case with a climate-induced reduction in future water availability.

- It will be difficult to replace the lost Two Forks Reservoir with other new storage facilities due to federal land ownership in Colorado as well as environmental and other legal constraints. The lack of a simple, inexpensive way to augment regional water supplies makes the climate-change analogy stronger since the veto will have an impact on regional water planning for many years.

This case study may be instructive for understanding social response to climate-change-induced water shortages for several other reasons:

- The Denver metropolitan region is situated on the semi-arid western edge of the mid-continental Great Plains, where water has long been the subject of conflict and disagreement. This case study, therefore, focuses on a metropolitan region where water is already seen as a scarce resource.

- Like other urban areas in the western United States, Denver has experienced rapid population and economic growth, as well as suburban sprawl, during the past 20 years. This has resulted in increased demand for treated water, new service contracts between larger and smaller water provider institutions, and political and other pressures to promote water conservation. Also, like other western urban areas, Denver has had mixed results from organized conservation efforts.

- Denver is facing a real future water stress today due to the loss of the Two Forks project.

Denver is now in a situation that several other western U.S. urban areas may face in coming years should climate change result in reduced future water availability. The manner in which Denver responds to the Two Forks loss thus may provide useful lessons to these other cities in their efforts to plan for the possible effects of climate change.

INSTITUTIONAL RESPONSE TO CLIMATE CHANGE: OPTIONS

Several water management options are available to metropolitan Denver water providers in the aftermath of the Two Forks veto, options that could also be used as part of regional adjustments to increased long-term water resources scarcity resulting from future climate change. Policies and actions to adjust to future water supply scarcity (irrespective of the cause) can be classified as (1) water supply related, (2) water demand related, or (3) involving both demand and supply management (that is, organizational, bureaucratic, or jurisdictional change). Nonstructural response options obviously can be implemented much more rapidly than major supply-related structural options. However, since the time frame under consideration extends well into the next century, regional water providers may view structural options as necessary to meet future water needs.

Supply Augmentation Options

Additional surface storage has been the clear strategy of choice in the past for DWD and other providers, emphasizing structural supply augmentation. Very little groundwater use occurs in the Denver metropolitan area (U.S. EPA, 1985). Reuse of existing supply has received some attention. For example, the DWD built and operated a pilot water reuse plant for several years to demonstrate the feasibility of reuse but has no plans to develop an operational facility. New large-scale inter-basin transfers that have been proposed in recent years have not been well received in potential exporting basins.

Nonstructural supply-related options available to Denver providers include purchase and transfer of agricultural water rights, water rights exchanges, reservoir management, and conjunctive-use arrangements. Colorado cities have been transferring agricultural water rights to municipal uses for more than 100 years (MacDonnell, 1989; MacDonnell et al., 1990a). These transfers have typically involved agricultural lands adjacent to the urban area of use, although some recent transactions have involved more distant agricultural lands (Bowers, 1990). Exchanges allow a user to take water under another's water right in return for providing an equivalent amount of water at another location or time. Such arrangements as well as changes in reservoir storage rights and operating principles can facilitate more efficient utilization of available water supplies. There are also opportunities for increasing the usable water supply through conjunctive-use management involving improved integration in the use of surface water and groundwater resources (MacDonnell, 1988).

Demand-Based Options

Demand-related options include structural conservation measures such as flow restrictors in faucets and shower heads and stricter water consumption requirements for new residential construction. Demand-based options also include a nonstructural tool: water pricing. Metering and alterations to rate structures can affect domestic water consumption. Outdoor use has been found to be particularly sensitive to price increases (Howe and Linaweaver, 1967; Hanke, 1970). Since outdoor use constitutes a major proportion of Denver water consumption, elimination of flat water rates and introduction of higher marginal prices may substantially reduce consumption, particularly during the high-demand summer months.

Stricter land-use planning and zoning practices constitute another nonstructural conservation option. Because of Denver's semi-arid climate, the use of governmental policies to influence land-use decisions represents a potentially powerful mechanism for promoting conservation. Public education on water conservation is another nonstructural demand-based option, perhaps made more effective when coupled with structural and pricing measures.

Other Options

Other available options are political and organizational in nature. This includes such options as the formation of new water provider alliances to merge water supplies, distribution systems, and customer bases; changes in institutional requirements concerning water supply or pricing; or changes in legal rules concerning water development and use. Distributional changes might include consolidation of smaller special districts into larger entities to take advantage of economies of scale or to moderate increases in water rates. A dramatic option in this vein could be the merger of metropolitan Denver water providers, including the DWD, into a truly metropolitan water agency.

Influences on Institutional Responses

Three groups of factors have significantly influenced, and are likely to continue to influence, which supply-and-demand, structural, and nonstructural alternatives are adopted by water provider institutions and local governments in response to the Two Forks veto. These factors are (1) Colorado's water laws and water rights, (2) environmental protection laws and contemporary environmental awareness, and (3) the historical water provider system and degree of providers' dependence on DWD.

Water Laws and Water Rights

The doctrine of prior appropriation that Colorado follows encourages those seeking legal rights to use water to do so at the earliest possible time and for the largest supportable quantity of water (Williams, 1983). Secure rights depend on physically appropriating water through diversions or storage facilities and applying that water to a "beneficial use." Under Colorado law, cities in particular are given considerable leeway between the time they claim water and when they must put that water to a direct use. Thus, for example, some of the water rights associated with the Two Forks project originally were established in the 1920s.

Appropriative water rights in Colorado are regarded as property that may be sold or transferred to others for their use (MacDonnell, 1989). In addition, the purpose or place of use of a water right may be changed to a different use, allowing water rights previously used for irrigation, for example, to be changed to urban use. A recent study has documented that changes in water rights of this kind are common in Colorado (MacDonnell et al., 1990b).

This legal structure will affect the manner in which water providers respond to the loss of the Two Forks water supply, or perhaps to climate-change-induced resource reductions. Water storage remains the best option for acquiring legal rights to large quantities of water under the water rights system, but there is little unappropriated surface water available in Colorado. Groundwater development rights are now better defined, but development of tributary supplies is limited because of the junior priority they would hold; development of more secure nontributary sources ultimately is limited because this is essentially a nonrenewable supply due to low rates of recharge. Water rights transfers are common in Colorado but have been used primarily to shift the uses of relatively small quantities of water in urbanizing areas.

Environmental Laws and Awareness

The convergence of environmental protection laws and regulations with public concern for environmental protection creates a new context in which water provider institutions must operate today and in the future. The EPA's veto of Two Forks dramatically demonstrates the new complexities of water project planning and development.

Other environmental policies and pressures from individuals and groups interested in environmental preservation increasingly constrain the water provider's latitude in expanding the supply side of the water equation. Minimum instream flows for fishery maintenance and other purposes are now an established part of the water management landscape. There are also pressures to reserve to the federal government water rights associated with federal lands in the western states. Water quality concerns are also growing, particularly as a result of groundwater contamination by industry, government, and agriculture; and surface-water contamination from mine drainage.

Increased awareness that water is a scarce resource in the western United States has caused many urban dwellers to recognize the value of preserving natural streamflows, wetlands, and other resources. This in turn has contributed to pressures on water managers to change their thinking (Frederick and Gibbons, 1986; Reisner and Bates, 1990). As a result, providers now consider water-demand management as a necessary means of supply augmentation.

Historical Setting and Dependence on DWD

The degree of dependence of some providers on DWD can be expected to have an inverse effect on their ability to seek more secure water for their respective customers. For example, Aurora's independent water department has the advantages of size, financial resources, and experience in obtaining agricultural and other water rights for transfer to its municipal customers. On the other hand, small special districts contracted to DWD are likely to remain dependent and simply adapt to whatever pricing, conservation, or other policies that Denver may introduce. A possible outcome is that the independents may be inclined to cooperate with each other in pursuing structural, supply-side responses while those more dependent on DWD may be compelled to move toward greater demand management in lieu of involvement in a systemwide solution.

RESPONSES SINCE THE VETO THREAT

Since metropolitan water providers first learned in March 1989 of the possibility of losing the Two Forks project and its subsequent veto, there have been several significant regional developments. Some of these were blatantly political, intended to pressure the EPA into backing away from the announced veto process. Others have been clearly adaptive, signaling institutional recognition that in the future water resources management must be conducted according to different rules.

In addition to the loss of Two Forks, other constraints on water development by metropolitan Denver's water provider organizations have become increasingly important in recent years. The question of reserved federal water rights for existing and new wilderness areas is currently in litigation in the Colorado Water Court (Colorado Water Court, 1977). The water project planning process nation wide has been clouded by the EPA's handling of the Two Forks project. Legal and political conflicts are probably unavoidable over proposed large-scale inter-basin transfers within the state to bring additional water to the Front Range (Frazier, 1991). Urban competition for senior agricultural water rights is likely to increase, as well as rural efforts to fight the cities; and sales of agricultural rights to cities have already affected the welfare of some rural communities (Foster, 1990a; Bowers, 1990).

Clearly, there is more at work here than simply the Two Forks issue. However, coupled with that controversy, regional water providers face a vastly changed water planning future: The loss of Two Forks has obliged water providers to confront the long-term collective impacts of these other constraints and to recognize that traditional answers to increasing demand are no longer operable. Since the announcement of an EPA intent to veto Two Forks, the beginnings of short-term and long-term institutional adjustments are evident. On April 4, 1989, the DWB adopted a resolution that states in part,

> [T]hose who have previously relied upon Denver for water service should begin immediately to consider independent options for future water expansion...the Board will continue to provide water for new taps within the City and County of Denver as required by Charter, and no shortage of taps for Denver is anticipated.... However, the Board's ability to share those supplies beyond Denver and limited contractual commitments will be diminished... (DWB, 1989).

Although the DWB's statement was partly inspired by a desire to pressure EPA to reconsider the Two Forks veto, the resolution has also become a signal to water providers dependent on DWD that their long-term reliance on Denver water may not be secure.

There have been other water provider responses to the EPA's veto announcement as well as the DWB policy resolution, including new jurisdictional alliances (*Rocky Mountain News*, 1990a); discussions of new urban/suburban purchase of agricultural water rights; and a lawsuit brought against the DWB by suburban water providers over inequitable water rates (Verrengia, 1990). The DWD has also pursued water conservation more aggressively, including implementation of increasing block-rate prices (*U.S. Water News*, 1989), dissemination of information on xeriscaping, a rebate program to encourage the installation of water-saving toilets (Obmascik, 1990), and accelerated metering of presently unmetered Denver residences (Hutchinson, 1989). It is likely that conservation will receive greater attention throughout metropolitan Denver.

The large-scale inter-basin transfer projects that have been proposed as the answer to Denver's future needs (Cantwell, 1990a; Foster, 1990b) are opposed vigorously by environmental and agricultural interests and are unlikely to proceed in the near term. In addition, while the DWB and some other Two Forks supporters have proposed a "mini-Two Forks" reservoir, less than half the size of the original proposal (Day, 1990), several original Two Forks participants have terminated their involvement (*Rocky Mountain News*, 1990b).

There is evidence of both conflict and cooperation following the Two Forks veto. The Northern Colorado Water Conservancy District recently completed a 2-year study of water supply and demand in several Denver metropolitan suburbs. The district's report suggests that with regional water sharing and greater conservation, additional water supplies would not be needed by several cities and towns north of Denver until about 2015 (Kerwin, 1991).

CONCLUSIONS

The Denver metropolitan region's adjustments to the Two Forks veto constitute an instructive case study of possible regional responses analogous to those that might occur because of climate change. Other metropolitan areas in the western United States (and perhaps elsewhere) that may face similar long-term water supply impacts in the future due to global warming may benefit from assessing the responses of Denver area water providers to the Two Forks veto. Of course, just how much other metropolitan areas may learn from the Denver experience depends on both similarities and differences in circumstances. The more similar the institutional setting in another metropolitan area (multiple providers, dominant water distributor, etc.) the more useful it would be to monitor and evaluate the Denver experience and to assess both opportunities and constraints.

The Denver experience is a story still early in the making, but there is already evidence that regional water providers are taking action to prepare for the long-term future. Increased attention to conservation and to pricing reforms is already evident in the Denver metropolitan region (Cantwell, 1990b), as is increased interest in agricultural water rights.

The Two Forks veto is a long-term shock unique to the Denver metropolitan region. The setback differs somewhat from the potential effects of global warming in that the size and direction of the impact on local water availability are not in doubt. Yet, the situation does illustrate the range of water supply response options available to other metropolitan regions if serious planning were undertaken in anticipation of future climate change and possible associated resource impacts.

The Denver metropolitan region's adjustments to the Two Forks veto will highlight the sources of regional conflict and cooperation over a valuable natural resource whose availability may be affected by climate change. The recent responses to the Two Forks veto suggest certain major trends in regional planning for future water availability. Because the Denver metropolitan region already faces an effective reduction in future water supplies, its responses will provide useful lessons on societal capacities to adjust to the possible consequences of climate change.

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ADAPTIVE RESPONSES TO CLIMATE CHANGE
EXTREME EVENTS SESSION

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The authors characterized the recent past hydrologic period as one of great variability. In fact, the variability has been extreme. Water resources system response was designed in the past partly in response to the understanding of climate patterns, particularly some degree of variability, that existed then and in the prior historical period. System failures or near-failures drove much water resources planning. We have inherited those systems; systems that predate our recent experiences (as in California) and call into question our ability to use them effectively to meet societal demands within the limitations potentially posed by climate change. Climate events that shift from their more-or-less-predictable patterns and their subsequent management responses have the potential to affect not only planned practices but the public's expectations and demands, producing conflict if not adequately resolved. Our management of these systems would be helped by our improved ability to predict weather events, particularly extremes, in both the near and longer term. In spite of climate modeling efforts, we lack such abilities, especially at the regional level. Given this limitation, yet needing to move forward in an environment that will probably preclude much infrastructural enlargement, we face a clear need to increase the public's awareness of both the constraints in system management and our limitations in weather forecasting. Simultaneously, the development of adequate forecasting tools must proceed.

Extreme events are probably more important in planning for potential climate change than relying on the mean. The public's focus on short-term events may hinder its recognition of longer term system changes. Since systems are inherently complex and climate change may be unprecedented, near-catastrophic regional events may obtain before a consensus for action occurs. However, we should be prepared to deal with these directly and to take anticipatory, preventative measures. This creates an obvious dilemma, for without a mandate for the latter we risk waiting for the former. With changing water demands and climate affecting the hydrologic and larger environmental systems, new management strategies may be required. The authors recommended that it will be necessary for resource managers to have operational flexibility--to be able to be adaptable, hopefully ensuring system reliability.

ADAPTIVE RESPONSE TO EXTREME EVENTS: PRESENT AND FUTURE

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ABSTRACT

During the past 10 years, hydrologic conditions in California have included the greatest seasonal snowpack, the wettest consecutive 2 years, a flood of record, and most recently, the driest 5-year period (still in progress) in nearly 60 years. The variability of both annual and seasonal runoff for the American River has been higher in recent years than earlier in this century. Major flood events have occurred more frequently in the past 40 years and with greater magnitude.

We do not know if this pattern of hydrologic variability will continue. If it does, the additional uncertainty about the magnitude of future extreme events will have a significant impact on the operation of existing multi-purpose reservoirs. The need for flexibility to meet changing conditions, necessary in the West even if the climate is not changing, would be even greater with additional uncertainty about the occurrence of extreme events. Effective adaptive responses by the community will depend on how credibly water resources decision-makers acknowledge the knowns and unknowns in system capability in a more uncertain climate.

This hydrologic variability has raised the public's awareness of extreme events and emphasized the need for better forecasting capability with longer lead times. The existing factors that limit our present ability to fulfill this need can also be expected to predominate in the future: Weather patterns beyond 2 weeks are likely to remain unpredictable, and extreme events will continue to be more significant than trends in the mean for water resources planning and management.

Operational decisions during both floods and droughts are a more frequent subject of public debate as multi-purpose water resources systems try to cope with increasing demands. Recent extreme events in California have statistically changed the levels of flood protection provided by existing facilities. If global climate change is occurring, and if this change results in greater hydrologic variability, additional operational flexibility will be needed. Public acceptance of operational decisions will depend largely on our ability to characterize the risks of flood damage, water supply shortages, and environmental impacts.

A key question in assessing these risks is whether the climate variability in the recent past will adequately describe future weather patterns. For the most part, recent practice in water resources system design and operation has assumed that the past record is a good guide to the range of possibilities that may occur. We size flood control and water supply facilities based on the magnitudes of floods and severity of droughts of the past and the likelihood of their recurrence. We describe the risks of flood damage and water supply shortages based on the past hydrologic record to achieve consensus on projects during the planning process. After construction, we allocate water supply based partly on reservoir storage levels, partly on probabilistic forecasts of runoff, and partly on the need for carryover storage in subsequent years. We acknowledge a considerable amount of uncertainty in seasonal weather forecasts and follow conservative allocation rules. Underlying each of these activities is the assumption that the climate is not changing.

Communication with the public is an important part of the process. Reservoir operations that attempt to balance flood protection, water supply, power generation, and fish and wildlife needs are scrutinized closely by a concerned community. Often project operations affect segments of the community in different ways. For example,

those most concerned with flood control are often not the primary users of water supply. The public's interest in water conditions becomes even more active during extreme events. During droughts, we seek to gain community support of voluntary or mandatory conservation measures. During floods we make every effort to accurately describe the risk of flooding so that appropriate emergency response measures can be followed. Again, interpreting past experience has been our best guide to what is likely to occur during these extreme periods. We do our best to inform those impacted by water management decisions that a significant amount of uncertainty exists in our projections of future runoff. We talk more in terms of odds and chances than in predictions. We recognize that there is limited skill in predicting weather patterns beyond about 2 weeks, and only modest skill beyond a few days. We know that our runoff forecasts are only a guide for what is likely to occur, and encourage water resources managers to also consider the forecast probability range to evaluate risk rather than relying on the median forecast.

If the global warming scenarios before us now come to pass, water resources managers and the public at large will have a substantially greater degree of uncertainty to contend with. Results of recent simulation studies (Lettenmaier and Gan, 1990; Lettenmaier and Sheer, 1991), based on general circulation model (GCM) climate scenarios that assume CO_2 doubling, indicate that major changes in runoff patterns are possible in California due mainly to temperature increases. The authors emphasize that these results must be considered sensitivity analyses rather than predictions because of the difficulties in matching coarse-grid GCM results with fine-grid watershed models. The results show a higher fraction of precipitation occurring as rain with a corresponding decrease in snow accumulation due to a warmer climate. Fall and winter runoff would increase and spring and summer runoff would decrease under this scenario. Lettenmaier and Gan (1990) report increases in peak flood flows due to warmer temperatures. In this study, hydrologic response compared to base conditions was greatly dependent on the geologic and topographic characteristics of the watershed.

By itself, a reduction in snowpack and shifting of runoff from spring to winter would have a significant impact on reservoir operations in California. The snowpack is a natural reservoir that satisfies a large part of the spring and summer demand. Reduced snowmelt runoff would substantially decrease the natural water supply when the demand is the highest. If reservoirs were required to provide increased flood control space to accommodate larger flood flows, the risk of shortages would increase dramatically.

The task of planning for future climate change would become easier if the GCM projections of warming and precipitation changes could be validated on a regional scale. We could then begin to evaluate these scenarios with respect to individual watersheds and whether existing reservoir storage could be reoperated to fit the projected runoff pattern. We could also begin the dialogue on new projects or modifications to existing facilities that a changing climate would require.

Before effective actions can be suggested, we need to be able to estimate how the frequency and magnitude of future floods and droughts are changing on a regional scale. Here we are faced with another difficult detection problem, in some ways more critical than the problem of detecting whether global warming has begun. Detecting changes in variability also may be more critical than being able to detect the trend in the mean on watersheds that do not have a large ratio of storage to runoff. Within the streamflow and precipitation records available for statistical analysis are periods of great fluctuation and relative stability. Given the extremes in California streamflow during the past decade, an obvious initial question to ask is whether we have evidence that recent conditions are more variable than earlier periods.

Figure 1 shows the distribution of the wettest and driest 25 percent of the record by decade for water year runoff on the American River. The decade ending in 1990 had the greatest number of wet or dry years, one greater than the decade ending in 1920. There was a period of relatively few wet years in the 1920s through the 1940s and a period of relatively few dry years in the 1940s through the 1970s. Note that although the 1970s had only 2 dry years, they were the driest 2-year sequence of the century (the severe 1976-1977 drought).

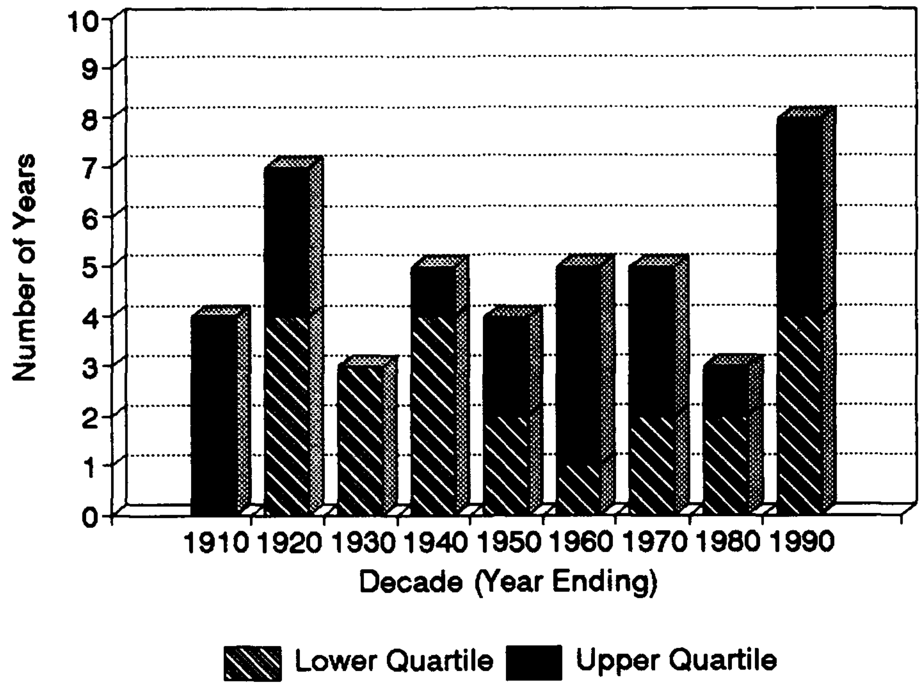

Figure 1. **Distribution by decade of the driest and wettest 25 percent of the annual unimpaired runoff record for the American River at Folsom Reservoir, 1901–1990.**

Figure 2 is a similar chart showing the occurrence of the wettest and driest 10 percent of the record. The distribution of these extreme years again shows that more have occurred in the past decade. Water year 1991, not included in this chart, would also be within the driest 10 percent of the record. Many of the dry quartile years during the 1911-1940 period shown in Figure 1 are not as extreme as those in the past 30 years.

Figure 3 shows the computed variability for 20-year periods by season for the same watershed. A 20-year period is a compromise between a short period with more fluctuation and a period that provides a long sampling base. Winter runoff and spring snowmelt are both showing more variability in the recent past than earlier in the century. An increasing trend in peak annual 3-day inflow from rain floods is shown in Figure 4. Of the 10 largest rain-flood events this century, 7 have occurred since 1951 (U.S. Army Corps of Engineers, 1991).

Another period of relatively great variability apparently occurred in the middle 1800s. Figure 5 shows that the period between 1850 and 1870 was even more variable than the past two decades based on Sacramento precipitation data, one of the longest station records available in northern California.

We do not know if the pattern of hydrologic variability seen in recent years will continue. If it does, the additional uncertainty about the magnitude of future extreme events will have a significant impact on the operation of existing facilities. The need for additional flexibility to meet changing conditions is one of the most frequently cited needs for water projects in the West, even without the prospect of climate change or increased climate variability. Increasing demands, decreasing likelihood of new surface-water development, and a greater emphasis on fish and wildlife needs have underscored the need for operational flexibility. Add to that the prospect of greater uncertainty in hydrology, and the need for flexibility becomes even clearer.

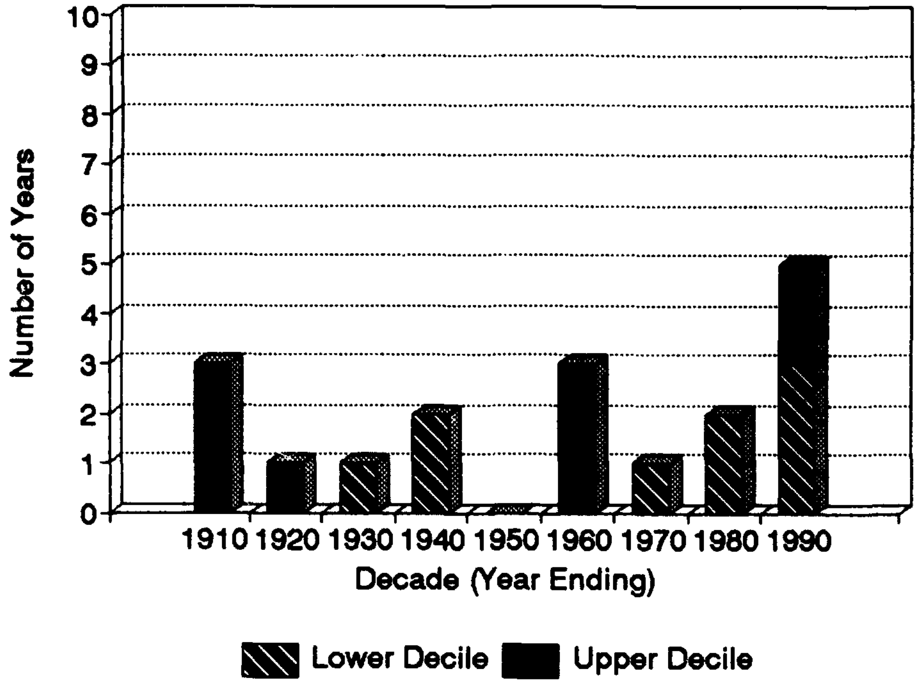

Figure 2. **Distribution by decade of the driest and wettest 10 percent of the annual unimpaired runoff record for the American River at Folsom Reservoir, 1901–1990.**

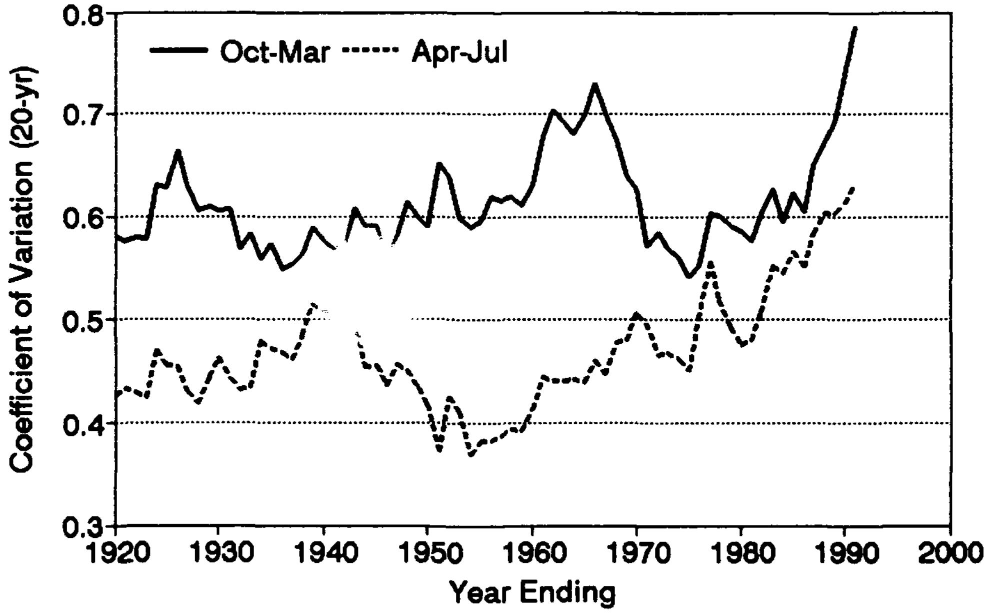

Figure 3. **Change in variability for winter (October–March) and spring (April–July) of the unimpaired runoff for the American River at Folsom Reservoir for a moving 20-year period (1901–1990).**

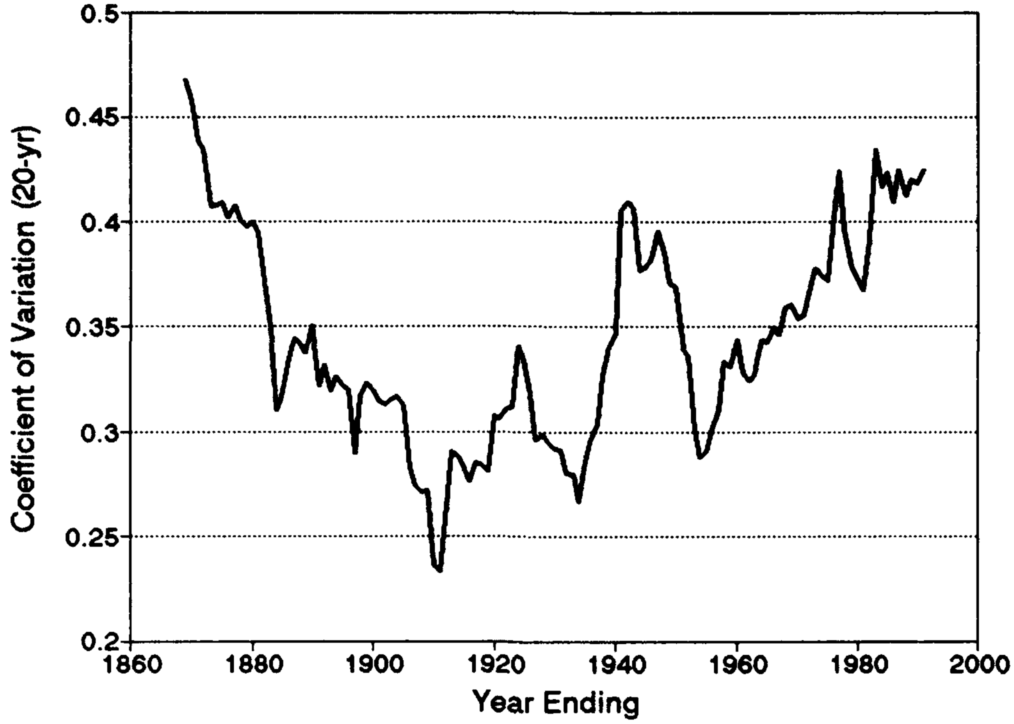

Figure 4. **Annual series of maximum unregulated 3-day winter rain flood events for the American River at Fair Oaks.**

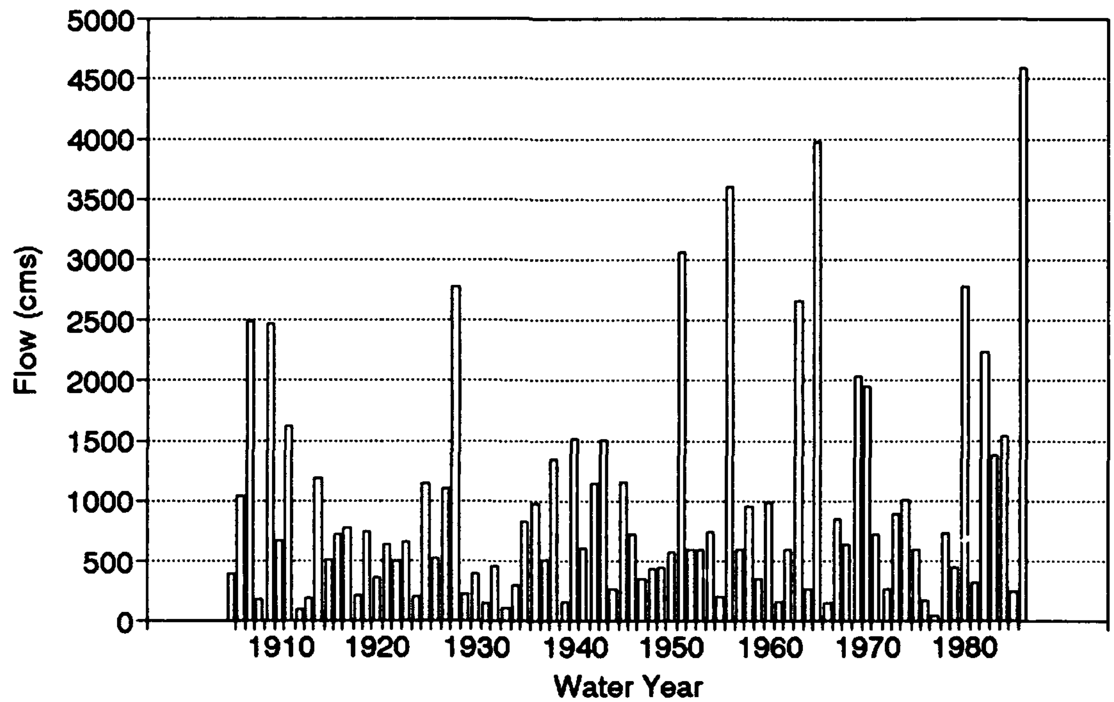

Figure 5. **Variability of annual precipitation in Sacramento for moving 20-year periods, water years (July 1–June 30) 1850–1991.**

Providing flexibility will not be easy without additional storage. If the trend of larger winter rain floods continues, more flood control space will be required, reservoir carryover capacity will decrease, and the risk of water supply shortages will increase. Quantifying the risks of floods and droughts so that a public consensus can be achieved, already a complex issue, could become even more difficult. Effective adaptive responses by the community will depend in large measure on how credibly water resources decision-makers acknowledge the knowns and unknowns in system capability in a more uncertain climate.

The issue of whether the variability of the past decade is a short-lived anomaly or evidence of an unprecedented change in climate is open to debate. We still do not know what the regional effects will be. The connection between the varying scenarios of temperature changes projected by general circulation models and the intense Pacific weather systems that have historically brought us major rain floods is not clear. Lettenmaier and Gan (1990) showed that the hydrologic response on a given watershed could be quite different depending on its physical characteristics. Specific changes in storm patterns relative to snow level, intensity, and duration will determine what actions are needed on each watershed. In order to respond effectively to possible hydrologic changes, project operators are likely to face difficult and unique choices among tools already available such as reoperation, new storage facilities, water banking and transfers, and demand reduction.

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THE ROLE OF EXTREME EVENTS IN ADAPTING RESOURCE SYSTEMS TO CLIMATE FLUCTUATION

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ABSTRACT

Extreme events are the chief driver of water resources system adjustment to environmental and social change. Two critical questions attach to the problem of social adaptation to extremes and to cumulative climate change should that occur: (1) How do resource managers perceive extreme events and how do complex water systems behave under stress and (2) does adjusting to extremes always improve water system ability to deal with future environmental and social change? Realistic assessments of water system adaptability in the face of change must include analysis of how system managers perceive change, system vulnerability, and response options.

INTRODUCTION

The history of water resources development in the United States is marked by legislative and engineering responses to extreme events. Mississippi River floods evoked the 1936 Flood Control Act, the 1930s drought became the "critical period" or "drought of record" for essentially every water system in the country, and Hurricane Agnes in 1972 ushered in federal flood insurance and contemporary ideas of floodplain management. While incremental and even forward-looking legislation and plans do occasionally emerge, water planning adjustment to environmental changes and stresses tends to be driven by system failures or near failures. In ideal situations, systems are designed to absorb events with probabilities as low as 0.01 without failing, and individual projects and critical facilities like spillways may be designed to handle events that occur, in theory, only once every thousand years or more, on average. A great deal of additional absorptive capacity, free-board, and over-design is added at various stages of project planning and implementation so that water system performance in the United States is remarkably fail-safe, with only an occasional dam breach, bogged-down river barge system, or urban water shortage.

But, how well can current systems handle really unusual events, or totally new distributions of hydro-climatological variables that would result from significant climate change? It seems likely that current system buffers and the development and redevelopment that occur on decadal time frames can absorb climate changes that would accompany global warming over the next several decades (as evidenced by, say, adjustments to 5 years of drought in California, or rapid recovery from the 1988 drought--see Riebsame et al., 1991). Nevertheless, how well water systems handle the extreme tails of current or altered climate distributions is likely to be an overriding concern in the near future as ability to enlarge or harden systems is reduced by political, fiscal, and engineering limits.

THE BEHAVIORAL PROBLEM IN UNUSUAL EVENTS

The focus of this brief note is on behavioral aspects of adjusting natural resource systems to extreme events. Unfortunately, even the most sophisticated engineering and risk-analytical approaches tend to neglect human behavioral factors; indeed, a long list of recent accidents in nuclear power plants, coal mines, airports, and shipping lanes has resulted from human behavior not anticipated in technical safety and reliability planning (Perrow, 1984).

System planning and management skills that fully integrate interacting social and environmental factors are poorly developed, as illustrated by management problems encountered in, for example, the 1983 Colorado River runoff, rapid Great Salt Lake and Great Lakes level changes, or the 1988 Yellowstone fires (Riebsame and Snajdarova, 1991). This bodes poorly for adjustment to future extremes such as water system vulnerability changes, and for adaptation to climate change that results in significantly altered frequencies and types of extreme events.

In a nut shell, the behavioral problem is that resource managers have difficulty anticipating how complex systems will respond to environmental stresses. This is because system response postures change over time with infrastructural aging and changing demands and rules; and because as systems have become more complex and interconnected, their response to any set of environmental stimuli cannot be as well defined (that is, their response sets become fuzzy or chaotic). In addition, manager experience and expectations also change over time. Yellowstone area fire analysts underestimated the potential for really big, hot, fast-moving fires in 1988 because of several decades of accumulated experience to the contrary (Fire Management Policy Review Team, 1988; Riebsame et al., 1991). In addition, the pattern of environmental stress can be intricate and even perplexing: recent problems in resource systems, like the 1983 Glen Canyon Dam emergency discharge or Yellowstone fires, involved short-term extreme events (strong winds or heat waves) imposed on cumulative climate conditions (multi-year drought or above-normal snowpack). The difficulty of assessing how natural and social processes will interact at different time scales, and how systems will respond, results in what Holling (1986) called "surprise."

MANAGING SURPRISES

Analysis of water planners' response to large swings in runoff in California's Sacramento basin (Riebsame, 1988) suggests that decision-makers focus on short-term solutions in a manner that can cause gyrations between policies aimed at system robustness (ability to withstand impacts without performance degradation) and resiliency (ability to bounce back after failure). The alternative is to focus on system adaptability (ability to alter elements, processes, and performance in unique ways over time). Thus, as demands on resource systems change, systems age, and climate change occurs, managers will be faced with the dilemma of responding in the short term to extremes in ways that improve (or at least do not degrade) system adaptability. Given increasing social and institutional constraints on infrastructural enlargement and other technological controls with large environmental costs (for example, pesticides, groundwater mining, etc.), and in the face of potential climate change, the paradigm of natural resources management will be shifted away from maximum yield, efficiency criteria, and fail-safe designs to adaptable and "safe-fail" approaches.

Several questions must be addressed as this paradigm shift occurs: Does the tendency to seek "single-tail" system safety after extreme events (such as drought proofing after dry spells or flood proofing after floods) result in systems that are inherently more robust? Is robustness achieved at the expense of resiliency or future adaptability? If the climate does change, are system managers willing to allow climate change to incur on safety margins originally established to deal with variability of a stationary climate? Can stake-holders be taught to accept greater output variability that naturally accompanies system adaptation?

Perhaps the key question is whether resource managers are willing and able to expand the range of options considered appropriate for future system configurations and performance. Only by reducing individual and institutional limits on "acceptable" performance, limits thoroughly inculcated in current training and practice, will resource systems evolve and thus avoid becoming fossil relics of past approaches (maximized sustained yield) that are out of synchronization with their changing social and physical climates.

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WATER QUALITY AND ECOLOGICAL SYSTEMS

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Joel Scheraga, Ph.D., Rapporteur

The speakers in this session focused primarily on problems related to water quality. They addressed regulatory, institutional, and legal aspects of water quality problems.

The consensus was that global warming both directly and indirectly could affect the integrity of the nation's waters, which the Clean Water Act is aimed at protecting. However, water quality and water supply problems exist that are unrelated to climate change, although climate change would exacerbate them (for example, change in temperature has implications for fish populations; sea-level rise has implications for saltwater intrusions--as in California).

How regulatory institutions will adjust over time given the scientific uncertainties about climate change has important implications for the effects of climate change on water quality. The participants identified as key uncertainties the community's understanding of equilibrium change at the scale of general circulation models, the effects of climate change at the "basin" scale, and the effects of climate change in transient conditions. For example, should regulatory institutions adopt changes in anticipation of climate change or wait to react? In fact, no regret options (water conservation, pollution prevention) exist that offer other environmental and economic benefits. But careful analyses must be made of any policy option, for tradeoffs exist between water quality, water supply, climate-change concerns, fish populations, etc.

KEY IMPEDIMENTS

Significant impediments exist to changing water management systems in response to expected climate change, as well as to other water quality concerns. These include the following:

- *Existing Laws*

Traditional concepts of water rights must be revised. However, legal impediments restrict the move toward more flexible systems.

- *Environmental Concerns*

Environmental interests may restrict the ability of planners to revise water management systems. For example, although strong arguments may be made that reservoirs should be built in anticipation of climate change, it is not likely that new reservoirs will be permitted in many areas (e.g. California).

- *Impediments to Water Markets*

Strong arguments can be made that more efficient water markets should be developed. However, states such as California are not likely to give up their ownership of water. Environmental concerns also compete for the water (environmentalists do not want that currently flows to environmental uses to go to other uses). Agriculture, which has a large demand for water, can be a powerful political entity (as it is in California). Also, water districts have considerable political clout. Finally, federal goals (e.g. concerns about climate change) often compete with state goals; similarly, agricultural, environmental, and municipal goals are often in conflict.

INNOVATIVE SOLUTIONS

Several innovative ideas were proposed by the session participants to improve water management systems. These included the following:

- *Modification of Streamflow Statistics*

It was argued that state agencies need to develop a greater capacity for developing streamflow statistics. Research on statistical hydrology was encouraged, and enhanced training opportunities for state researchers advocated.

- *Flexibility in Setting Stream Standards*

The consensus was that regulatory institutions need to confront the legal and institutional barriers that currently prevent them from setting more flexible and efficient stream standards. The speakers suggested that removing barriers would allow for more comprehensive benefits work that in turn would lead to more meaningful standards. Discharge permits might be revised to reflect changes in instream conditions, and the focus of non-point-source programs could change over time.

- *Homeostatic Control of Emissions*

The speakers suggested that studies be conducted of adaptive control strategies, variable-cost intensive control technologies, and inframarginal quality benefits.

- *Revision of Water Rights*

The strong consensus was that existing systems defining water rights need to be revised, especially in those areas of greatest stress. To accomplish this, however, the key impediments outlined above must be eliminated, and a stronger legal basis for more flexible systems must be established.

ADAPTATION OF WATER QUALITY SYSTEMS TO POTENTIAL CLIMATE CHANGE

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ABSTRACT

Climate change could have substantial effects on the quality of water resources world wide. Some waters might be improved by potential changes in regional climate, but likely most would not. The severity of possible degradation will depend to a great extent on the response of water use systems and environmental controls. Thus, foreseeing the effects of climate change on water quality is difficult not just because of poor understanding of future global mean temperature, and associated regional climate variables, but because of a lack of knowledge of how public perceptions will evolve and the ways that regulatory institutions will adjust under long periods of uncertainty.

This paper reviews the state of climate prediction at the regional level, and the likely time path to greater understanding. Concentrating on traditional water quality concerns, mainly the levels of artificial and natural chemicals in surface and groundwaters, it then discusses desirable patterns of adaptation considering the long lead times in the climate system and the likely long wait for clarity about the sign, much less the magnitude, of key regional variables such as rainfall and runoff. The focus is on flexibility and the avoidance of potential big mistakes along the way.

INTRODUCTION

The effects of climate change on water quality would be many and varied. This paper considers the potential implications for water management of just one aspect of this problem: its effect on the capacity of surface waters to accept anthropogenic and natural pollutants. An important function of streams, estuaries, and lakes is their ability to remove waste from points of generation, to dilute concentrations and thereby reduce the potential for environmental damage, and to serve as a medium where pollutants are degraded or destroyed. Much of water pollution control policy is directed to controlling the load on these water systems in order to keep the adverse effects on the water environment within acceptable limits.

If climate change lowers runoff, or changes its temporal distribution, the problems of managing this aspect of water quality will increase, along with the costs of sustaining acceptable quality standards. If, as appears unavoidable, water quality management must proceed for the next several decades in the face of great uncertainty about potential effects on surface hydrology, then the proper adaptation of water policy and management practice becomes even more problematic. The purpose of this exploration of the climate/water issue is to set the stage for discussion of ways that water quality management may be called upon to adapt over time and of what might be done now to prepare for difficulties that may lie ahead.

THE EFFECT OF CLIMATE ON QUALITY MANAGEMENT

The Control Regime

In the United States and many other countries, the quality of waters is determined by their suitability for "use" by cities, industries, and individuals. Under U.S. legislation, for example, each body of surface water must be put into one or another quality class. The U.S. Environmental Protection Agency publishes criteria that specify the conditions deemed consistent with specified uses. State authorities then establish broad water use classifications (public food processing, water supplies, swimming, indigenous aquatic life, etc.) and apply the federal criteria in determining standards that must be met within each class. (Separate guidelines, standards, and legislation apply to groundwater.) Prior to 1972, these instream standards were the dominant feature of U.S. water quality legislation. But frustration with slow progress under a pure "standards and state enforcement" approach led Congress to impose a set of nationwide treatment requirements that hold regardless of the condition of the receiving waters.

State implementation of instream standards now takes place in the context of these mandatory treatment levels. Pollutants are divided into three categories: (1) conventional, including biochemical oxygen demand or BOD, suspended solids, acidity, and fecal coliform bacteria; (2) toxic; and (3) nonconventional, including everything outside the other two categories (mainly nitrogen, phosphorous, and ammonia). Conventional pollutants from point sources must be treated by Best Conventional Technology or BCT, which essentially is standard secondary treatment. (Secondary treatment normally includes screening, settling, and some form of controlled biological oxidation of organic matter. The technology does not allow much of a cost-removal tradeoff once the facilities are built.) Point-source discharges of toxic and nonconventional pollutants are to be treated using the Best Available Technology Economically Available, or BAT. The determination of what BAT means for a wide and growing list of toxic substances has been a long saga of congressional mandates, missed deadlines, and law suits. The stipulation of discharge standards for these chemicals is still under way. The enforcement of the BCT and BAT standards is carried out through the National Pollution Discharge Elimination System (NPDES). Every point source of pollutants must have an NPDES permit, which requires evidence that the relevant BCT or BAT standards are met.

If, after the imposition of BCT and BAT controls, ambient standards are not met for particular waters, then states must impose other measures. Depending on circumstances, these might include more stringent treatment of existing discharges, restrictions on the growth of polluting cities or industries, or the prohibition of certain technologies or forms of economic activity. Under federal law, state authorities must formulate and implement these plans, or risk federal takeover of water pollution control functions. (States also must worry about nonpoint sources of pollution, such as agricultural runoff, mine drainage, construction, and saltwater intrusion. The regulatory machinery is primitive compared to that for point sources.) In assigning classifications to individual streams, estuaries, and lakes, state authorities take into account the costs of attaining the standard set.

In the application of this legislation to rivers and streams, quality characteristics for each class are defined most often by maximum concentrations of unfavorable substances like salinity or toxic chemicals, and minimum concentrations of a favorable one, dissolved oxygen. Other indicators not defined as concentrations include temperature, radioactivity, smell, and color. For any rate of pollutant discharge, which is the industrial, municipal, and other waste generation net of any cleanup, instream quality depends on streamflow. Because the flow in rivers and streams may vary by a factor of 10 or more between low- and high-water periods, quality usually is defined for a critical low-flow condition.

Different definitions of the critical low flow are found in practice, but a common specification is the minimum 7-day average flow expected once in 10 years (Loucks and Jacoby, 1972). It will be used here for illustrative purposes, and denoted F. For any zone of a river or stream, the standards require that emissions be restricted so that instream concentrations of pollutants will not be exceeded so long as the actual flow is F or greater. Or, in the case of dissolved oxygen, a minimum concentration must be maintained under the critical flow. Whether a particular body of water meets the standard is determined by calculating the concentration from data on known (usually NPDES permitted) discharges and the critical flow. If calculated concentrations violate the standard, this same procedure can be used to calculate pollution restrictions that must be imposed to bring waters to the standard.

The Challenge If Climate Change Were Certain

A simple case of biological pollution and dissolved oxygen will illustrate the issues that potential climate change raises for this system. Dissolved oxygen is both a direct measure of the quality of water and an indirect indicator that other pollutants are present. Urban and industrial waste and agricultural runoff contain biodegradable material or BOD. As the material degrades (oxidizes), the oxygen in the water is reduced. If the BOD load is too high, and oxygen is drawn too low, oxygen-dependent life (like fish) will die. Warmer water holds less oxygen to begin with, and a warming of several degrees will itself lower quality, adding to any effect from reduced flow.

Figure 1 demonstrates these effects for an otherwise unpolluted stream with a single BOD load (say a city, which already meets the BCT criterion) at kilometer zero (Metcalf and Eddy, 1979, p. 842; Jacoby 1990). The upper curve shows the current level of dissolved oxygen given this discharge and current critical-flow F_1 and associated temperature T_1. The critical low flow is 10 m^3/sec, and the river temperature is 15°C. As the bacterial oxidation reduces the dissolved oxygen in the stream below its saturation level (which is 10.2 mg/l in fresh water at 15°C), a process of reoxidation or reaeration occurs. The interaction of deoxidation and reaeration yields the "oxygen sag," which the figure shows downstream of the discharge point. In this example, a water quality of 5 mg/l is maintained under conditions F_1, T_1.

The economics of standard setting and quality control in this situation are shown in Figure 2. It shows different quality classifications, A through D, and associates each with a particular critical level of dissolved oxygen. The numbers shown are for ease of exposition, and do not mimic any particular state regime. The figure shows the marginal costs of attaining the various quality classes under two different cost cases, both with critical flow F_1 and the temperature T_1. The case $MC_1(F_1, T_1)$ is one where the marginal costs to lower BOD loads upstream are relatively low; in the case labeled $MC_2(F_2, T_2)$, the marginal costs are higher. What classification is appropriate depends on the marginal benefits, MB. In the case of MC_1 the waters would be put in Class A. However, to put the waters in Class A under the other cost conditions would require very expensive controls, and they should be put in Class B.

In fact, of course, except in very special circumstances water quality management is not based on such a formal economic analysis. However, the layout of Figure 2 is a useful way to think about the process of classification and control, because in a rough-and-ready way this is what happens whenever waters are classified under something lower than the top category. An implicit tradeoff is made between quality and cost. Climate change likely would make this choice even more troublesome than it is today.

Using this simple example, and taking MC_1 as reflecting the marginal costs under undisturbed climate, consider the problem that arises if climate change affects local hydrology and temperature. One effect of a shift in climate will be changed streamflows, the most important being the critical low flow. In some regions the critical flow may rise, increasing dilution and improving water quality. In others it may fall, reducing stream quality. Deterioration will occur wherever precipitation decreases or where increased evapotranspiration overwhelms any increase in precipitation. Quality also might be reduced under increased precipitation if wet periods are shifted back toward the winter and spring, leaving drier conditions in late summer when low flows occur in many regions (Gleick, 1987).

For the case in Figure 1, assume a 2°C increase in temperature to T_2=17°C, accompanied by a reduction in critical low flow by 25 percent to F_2=7.5 m^3/sec. The decrease in flow alone causes a reduction in dissolved oxygen. The minimum falls to around 3.5 mg/l, as shown by the middle curve. The increase in temperature raises

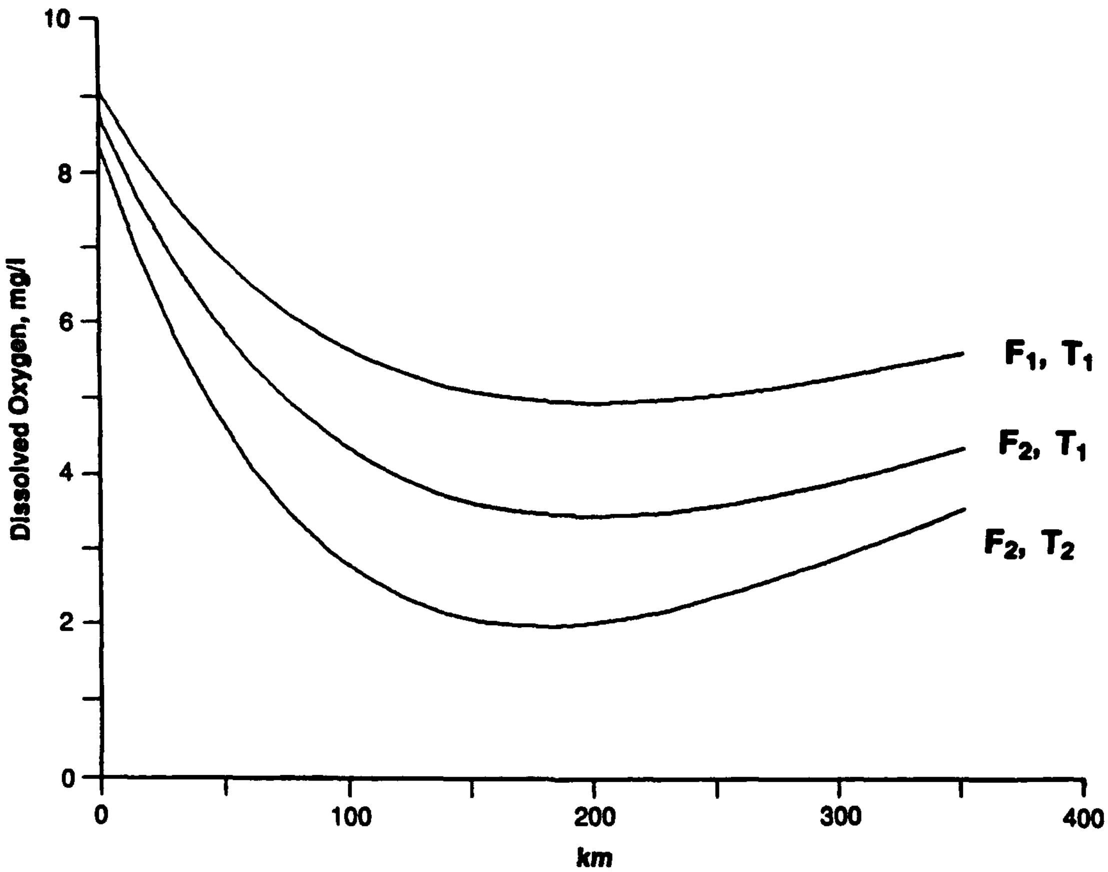

Figure 1. **Effect of flow and temperature on water quality.**

both the rate of biological activity (and thus of deoxidation) and the rate of reaeration, but the effect on deoxidation is the greater so the oxygen level is pulled down further, to 2 mg/l.

The implications for classification and control are shown in Figure 3. With the lower flow and higher temperature, the waste absorptive capacity of the stream falls, and higher control costs must be incurred to maintain quality standards at any of the levels shown. These costs may include increased costs of treatment, raised opportunity costs of restrictions on economic developments or particular technologies, or the costs of increased pressure on air and land resources as wastes are transferred from the waters to some other medium. The cost function shifts from $MC_1(F_1, T_1)$ to $MC_1(F_2, T_2)$. The possible responses are clear, and the choice should take account of the marginal benefits. Under the case in Figure 3, Class A can be maintained only at a cost far above the benefits gained by doing so. To avoid this outcome, the stream would have to be dropped to a lower class, and even then the control costs would be higher than before the change in critical flow and temperature. If they come about, such changes in flow would particularly affect the quality of streams in arid regions.

Warming plus a reduction in critical low flow will create problems in estuaries and bays similar to those in rivers and streams. In addition, the penetration of salinity from the oceans will increase. A crucial aspect of estuary quality is the front or boundary between fresh and salt water, and a shift in climate may yield changes in fresh-water runoff and sea level that will have a combined influence on the salt front.

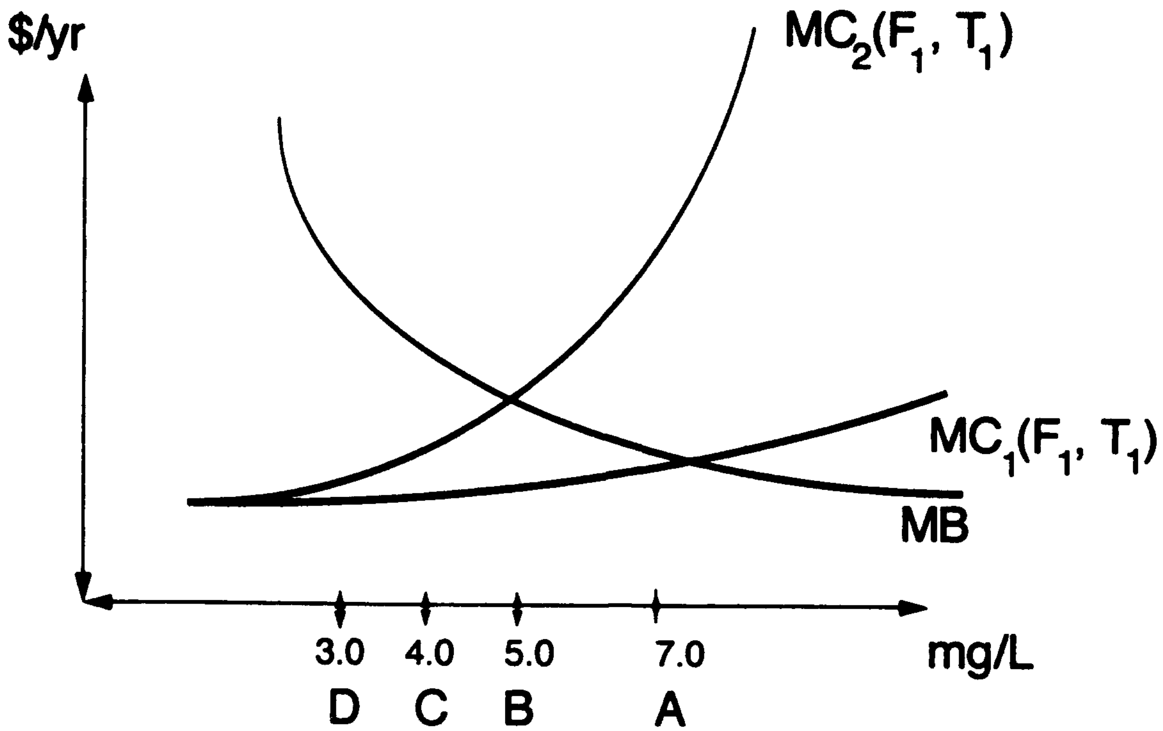

Figure 2. **Standard setting with different cost conditions.**

Lake quality also may be affected by changes in runoff patterns, and by temperature and evaporation. Lake quality also is influenced by changes in annual average and seasonal temperature and wind, and the associated dynamics of temperature stratification and seasonal overturn of waters (Jacoby, 1990). Pollutant concentration in a lake will tend to a level equal to the ratio of output water volume to input pollutant quantity. If inflow falls or evaporation increases, lake quality will fall, the time path of degradation depending on the volume of the lake. Large lakes, with longer residence times, will be sensitive to changes in mean annual flow of incoming streams and to changes in the likelihood of extended drought. The quality of small lakes may be sensitive to changes in seasonal or even minimum weekly flows. Groundwater resources may also be influenced by changes in rainfall and runoff (Jacoby, 1990).

In all these cases, changes in climate could present difficult tradeoffs between raising or lowering quality standards, and between increasing or decreasing the costs of emissions limits. If climate change brings reduced flows, the implications for some combination of stream standards and control costs may be very great because the percentage change in critical minimum flow will likely be some multiple of any change in climate variables such as temperature, precipitation, evapotranspiration, and soil moisture. For example, studies by Schaake (1990) using water balance models indicate that the elasticity of low flows (measured by average flows in the three driest months) to precipitation change can be as high as 4. The sensitivity to climate of a more stringent measure of low flow, like the minimum 7-day 10-year criterion, would likely be as great or greater.

UNCERTAINTY IN REGIONAL CLIMATE AND ITS LIKELY RESOLUTION

Because of the dependence of water quality on low-flow conditions, quantifying the effects of potential climate change on water quality may be one of the more difficult tasks of impact analysis. A cascade of uncertainties stands between the implications of climate change as portrayed in Figure 3 and the circumstance water managers might face in future years. The analysis of global change is fraught with difficulty, even for simulations of a few months of equilibrium climate at large scale. Yet streamflow is a basin-level phenomenon, which implies analysis on a fine scale, perhaps 10 to 100 km. Furthermore, analysis of variability and persistence, which requires long-term flow information, is crucial to the determination of extreme conditions under which quality standards are set. A brief review of some of these aspects of climate analysis will indicate the nature of the difficulty.

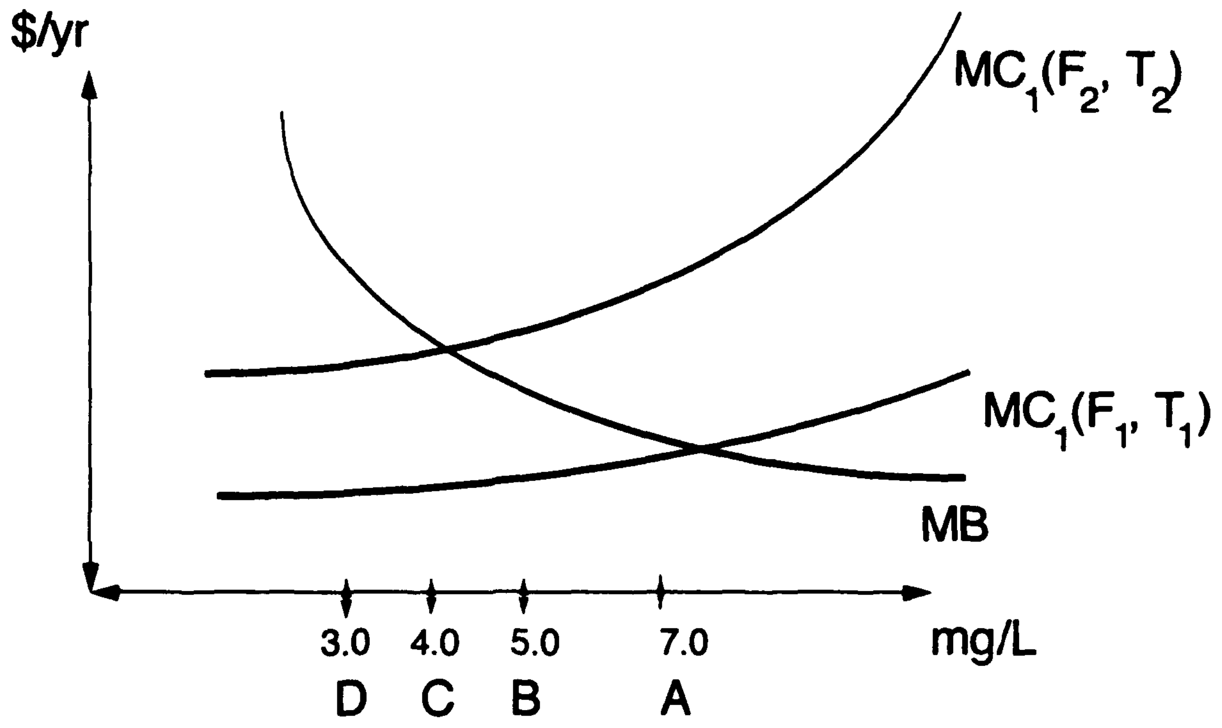

Figure 3. **Quality control with certain climate change.**

Equilibrium Change at GCM Scale

To begin with, greenhouse gas (GHG) budgets--past, present, and future--are not well understood. Current analysis of the processes of sequestration of CO_2 in the oceans and terrestrial biosphere cannot adequately explain the relation between emissions of recent decades and the concentrations now in the atmosphere, and forecasts of future emissions are subject to all the uncertainties of economic analysis and unresolved disputes over control policy. Moreover, much remains to be understood about chemical processes in the atmosphere that influence the lives of the various GHGs, their interaction, and their ultimate radiative effects.

Beyond the question of GHG budgets is an even more difficult issue of climate analysis itself. Despite large and growing investments in climate research and large-scale modeling, considerable dispute surrounds the results of the current generation of forecasts. The models themselves do not diverge greatly in their estimation of the effects of increased radiative forcing. Recent modeling studies show an equilibrium response of global mean temperature to CO_2 doubling of between 1.9°C and 4.4°C, with a clustering of estimates around 4°C (Mitchell et al., 1990). The dispute comes over the crude parameterizations in all these models of crucial phenomena such as cloud physics and ocean dynamics--a debate energized by the difficulty of explaining why model-forecast change exceeds observed warming over the past century. Substantial improvement in these areas appears to await both scientific research and an increase in computing power of several orders of magnitude.

Even GCMs that are in reasonable agreement about global mean temperature may be inconsistent at the level of regional climate variables, which is particularly troublesome for purposes of water quality. For example, Grotch and MacCracken (1991) compare the behavior on a regional scale of four GCMs. (A "region" in this case is a GCM grid box at the scale of current models, which is around 500 km on a side.) The four models are in rough agreement about global mean temperature increase with CO_2 doubling: Three cluster near 4°C and the fourth shows 2.8°C. At regional scale, however, they perform poorly. The study considered temperature and precipitation, and compared model results (assuming 1 X CO_2) with observations. The models are in rough agreement with observations on latitudinal variation of temperature (which GCMs simulate well) but they are unable to simulate longitudinal temperatures over land areas. The simulations of precipitation also are in considerable disagreement with measurements. When applied to a 2 X CO_2 experiment, the differences among the models are of the same order as the GHG-caused perturbations. Another example is an experiment by Kellogg and Zhao (1988), who got similar results when they compared five GCMs in simulations of precipitation and soil moisture for North America. Although they found modest agreement in the winter, the disparity in summer values was substantial.

Climate Analysis at Basin Scale

Even with improved performance at current GCM scale, the problem remains of analysis at a scale relevant to river basins. It may be possible on the basis of GCM results to say that a region will be generally "drier" or "warmer," but without smaller scale analysis it may not be possible to say by how much for particular water bodies. When it comes to adjusting water pollution policy, this question will be very important.

Several methods are under study for achieving results at smaller scale even while waiting for another generation of GCMs with greater discrimination. Some look to historical analogies (for example, how it might be if the drought of the 1930s were the norm); others try to take the coarse-grid results from GCMs and translate them to local scale using correlations drawn from climate observations. Both of these approaches have serious limitations (Giorgi and Mearns, 1991). More promising, at least conceptually, is a model-based method whereby a local-scale representation (which does better by features such as coastlines and mountain ranges) is "nested" or "imbedded" in a global model. In most of the work to date, GCM-scale variables set the boundary conditions for the more detailed simulation (a one-way connection). Models with feedback from the local to the global, where the small-scale solution is used to correct aggregation errors at the larger grid size of the GCM, are only now in the development phase.

These nested models suffer from shortcomings of their own (Giorgi and Mearns, 1991), not the least of which is the fact that the imbedded model multiplies the GCM demand for computer capacity. This problem is particularly acute when the concern is extreme conditions, like low flow, which would require many years of simulation to generate statistics comparable to those now used to define water quality standards. With current computers, these computations appear as intractable as the solution of GCMs at substantially finer scale.

Climate in Transient Conditions

All the concerns above apply to the problem of estimating the *equilibrium* response of regional climate to increased GHG forcing. If there is to be global warming, however, the relevant conditions for purposes of water management are not those of some long-run equilibrium but of a transition from one temperature regime to another. Conditions during a temperature transition might be very different from those at the ultimate destination for any given level of forcing, particularly for the hydrologic cycle. Because the oceans are a sink for heat, the temperature over the continents may rise faster than over water. Whatever the long-run equilibrium balance of precipitation and evapotranspiration, in the transition a greater warming over land would cause evapotranspiration (producing dryness) to run ahead of ocean evaporation (producing precipitation). The result would be a higher likelihood of drought.

Some indication of the possible magnitude of such an effect is indicated in a study by Rind et al. (1990). Using the GCM developed by the Goddard Institute for Space Studies (GISS), they compute monthly indicators of drought for a 100-year control run at 1958 forcings and under a scenario of continued exponential growth in GHG emissions. (The model is one that yields roughly a 4°C warming for doubled CO_2.) The results suggest that severe drought, which they define as that drought index value having a 5 percent frequency today, will occur 50 percent of the time by the middle of the next century. What these results may mean at basin scale, or for indicators of minimum flow, is not known. But the implication is that, if warming occurs, low-flow conditions will become more frequent, and perhaps more extreme, in many areas of the continent.

The Resolution of Climate Uncertainty

Given the current state of knowledge, then, the problem faced by water quality managers is more properly represented by Figure 4. Uncertainty about future climate change, and its basin-scale effects, translate into huge uncertainties about the future of water quality control. It is not known now how much it will cost to maintain current stream classifications, with their associated uses, or how far classifications might have to be reduced to keep some reasonable balance between the benefits of instream quality and the costs of sustaining them.

Unfortunately for those responsible for managing water quality, these uncertainties may not be resolved substantially ahead of the time when actual instream changes might begin to occur. Because of the natural variability of the climate system, there would be a lag between the time when any change in temperature actually occurred and the time it could be measured with confidence. The length of the lag is not known, but it may be several decades. If for purposes of quality management critical flow is computed using historical streamflows, as at present, then the lag would be substantially longer, maybe 50 to 100 years.

It would be possible to adjust climate-related parameters, such as critical flow and temperature, based on climate-model results of the type discussed above. The question that will arise, however, is what level of confidence in results is sufficient to justify changes in policy that may involve additional costs or revisions in quality standards.

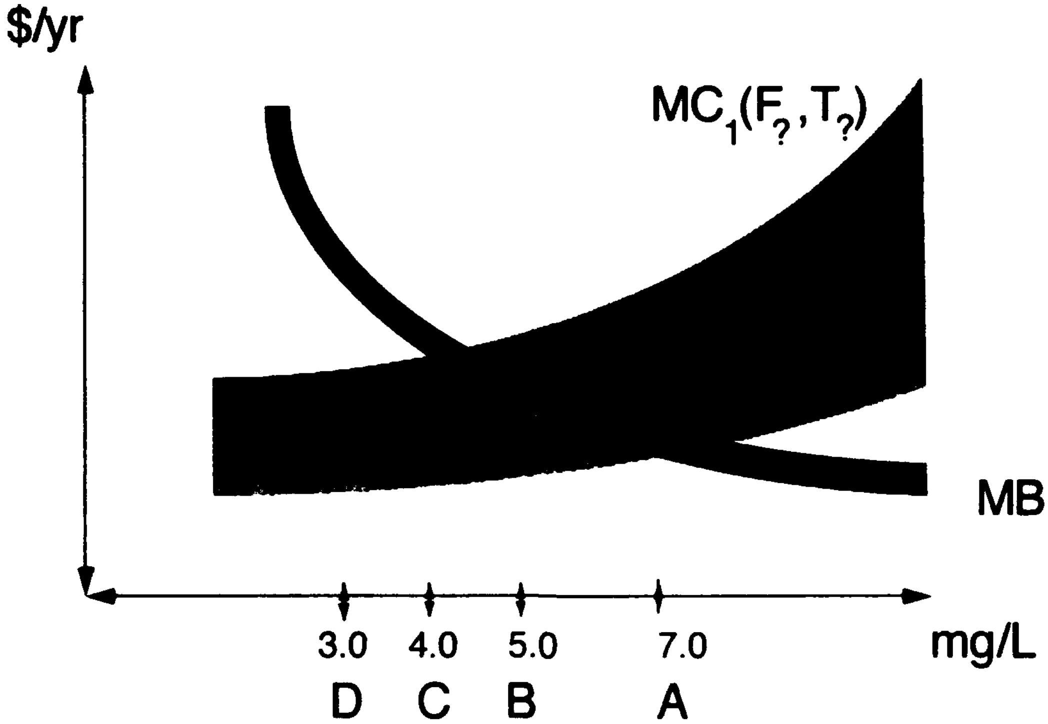

Figure 4. **Quality management with uncertain climate change.**

The process by which forecasting uncertainty may be resolved is itself highly uncertain. It depends on developments in research in physical, chemical, biological, and social science; on the outcome of continuing programs of measurement; and on progress in the construction of a new generation of climate models along with a new generation of computers to support them. Schneider et al. (1990) venture an estimate of the "time for research that leads to consensus." Although the concept of "consensus" is unavoidably vague, their opinion is nonetheless informative. They estimate a 10- to 50-year process will be required to produce agreement on the variables of interest here: precipitation, evapotranspiration, soil moisture, and runoff.

Thus, for the next decade or more there will be no easy guidance from either environmental measurements or environmental science as to how water quality management practices may have to be adjusted.

THE ADAPTATION OF POLLUTION CONTROL POLICY

Those responsible for the quality of the nation's waters must steer a course between two possible errors in dealing with the potential effects of climate change: too much too soon and too little to late. On the one hand, it is important to prepare for changes in control policy and practice that may be called for as uncertainty is reduced. On the other hand, in this circumstance of expectation of change, but great uncertainty about its magnitude and timing, there is a risk of hasty, poorly analyzed responses. A person needs considerable analytical sophistication and specialized knowledge in order to know that there is a difference between the climate and the weather. Extreme events (a drought for example) that are well within the distribution of conditions for undisturbed climate can nonetheless trigger heightened press and public attention and, possibly, strong political response. Substantial costs might be incurred, say by across-the-board tightening of BAT definitions or moratoriums on urban/industrial development, with insufficient evidence of compensating benefits or a need for them.

Four areas of adaptation seem most likely in the event confidence *is* established that significant warming, and associated change in runoff, is being caused by GHG emissions. If we are to have the capacity to carry them out in an efficient and effective way at any time in the next decade or two, then research, analysis, and training are called for now.

Modification of Streamflow Statistics

Although the past 30 years have seen major advances in the statistical analysis of streamflows and in the construction of models of synthetic hydrology (Fiering, 1967), the setting of critical flows, F, in many cases is still based on very simple processing of the historical record. (Frequently, the calculation involves no more than passing the historical flow record through a simple filter to compute a series of flows averaged over 7-day periods. The presence of storage reservoirs, omitted from this discussion, brings even greater need for analysis.) If anticipated (but not yet measured) drying is to be factored into the analysis of critical-flow conditions, then preparations are needed in at least two areas:

- Increased research on statistical hydrology, with a special focus on possible links to the types of results, even in a limited form, that may be produced by GCMs, perhaps run jointly with imbedded basin-scale models.
- Development of increased capacity within state water agencies to carry out statistical work on hydrologic series, and preparation of data bases appropriate to this task.

Flexibility in Setting and Revising Instream Quality Standards

When the current system of stream classifications was established, the expectation was that streams, once put in a class, would never be downgraded. Indeed, the pressure for change has been to bring as many waters as possible to the highest classification. In the future there may be a need for downward flexibility. To prepare for this eventuality, several things can be begun now:

- Renewed research on the estimation of the benefits of various levels of stream quality, and on practical ways that costs to maintain standards can be brought into a common analysis with the benefit data.
- Studies of the legal and institutional barriers to reclassification of waters to a lower quality level.

Homeostatic Control of Pollutant Emissions

As noted above, most water pollution control policies involve setting a permissible level of emissions under some set of critical conditions, F and T in the example here, and then holding dischargers to these limits under all conditions of temperature and flow, even when waters could accept more waste with little effect on instream quality. In part, this pattern results from the common technology of treatment, which is highly capital intensive: Once built it is run continuously. In part it is because of the operation of traditional source controls that prohibit an activity or technology altogether; it is not possible to turn on the activity when streamflows are high. And in part it is because of the NPDES itself, which ignores ambient conditions in the receiving waters.

If water quality officials can no longer operate on the assumption that a stable climate distribution underlies the definition of critical conditions, then the system as a whole may need to be revised in the direction of greater flexibility of control in response to stream conditions. It may simply be infeasible in some situations to maintain acceptable water quality at reasonable cost under a rule of "always operate as if flow conditions were at their worst."

A useful metaphor at this point is the system of homeostatic controls by which the human body regulates its functions in the face of changing environmental conditions. An example in water pollution control is the possible use of interruptible discharge permits, which would allow certain emissions when the waste absorption capacity of waters was high, but restrict them under low-flow conditions. Were effluent charges in use, they could be adapted easily to such a task, likely with substantial efficiency savings (Frederick and Kneese, 1990). Work in this area could include the following:

- Feasibility studies of adaptive control strategies that might be applied to water quality management, including analysis of how quality criteria and instream standards might be defined to accommodate the change, and study of alternative time scales over which flexibility might be exercised.

- Research on variable-cost-intensive treatment technologies that might be brought into play if flexible removal percentages were allowed.

- Research on the benefits to be attributed to increments of stream quality above the thresholds set for a particular quality classification. This is a benefit that would be eroded if flexible control strategies are applied, and the size of the loss needs to be understood.

Revision of Traditional Concepts of Water Rights

In the event of climate change that reduces runoff, the allocation of water to its highest and best use, including the maintenance of instream quality, will assume a greater priority than now. Today U.S. waters are governed by a complex tapestry of laws, compacts, and market arrangements, some of which are likely much better than others in achieving efficient allocation under stress (Trelease, 1977). In the event of substantial reductions in minimum flows, and changed frequency of these events, the needed rewriting of law, and reallocation of rights, might be substantial. To be ready for such an occasion, the following activities might be undertaken in the near future:

- Studies of the main areas in the United States where a shift in hydrology would put significant stress on the system of water law.

- Analysis of ways that laws could be changed to accommodate more flexible systems of water allocation, such as various forms of water markets.

This list is no doubt far from complete. But even this preliminary effort shows that advance work now can help ease the problems of adaptation should the need arise in the future, and it can help guard against ill-considered responses along the way.

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POLICY CONSIDERATIONS FOR WATER QUALITY PROGRAMS WITH REGARD TO GLOBAL WARMING

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ABSTRACT

Section 101 (a) of the Clean Water Act states that it is "the objective of this Act ... to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." Since this language was incorporated into federal law in 1972, the U.S. Environmental Protection Agency and state agencies have implemented an expanding variety of programs aimed at achieving this goal. My purpose today is to reflect on the possible threats to our nation's waters from global climate change and to consider ways in which our water programs could be adjusted to respond to these threats.

To begin, let's look at possible effects of climate change. I am assuming we are talking about changes driven by warming, though any widespread change in climate of the planet could have significant impacts on water resources and water-dependent biota. What kinds of changes would we be most concerned about?

First, of course is change in the water temperature itself. Since the vast majority of organisms living in aquatic environments are "cold blooded," their body temperature will change as their water environment changes. Increased temperature can cause a variety of direct effects on organisms, primarily through changing the rate of various biochemical processes, most of which are catalyzed by enzymes. Changes in the basic biochemistry of an organism can, of course, result in changes in physiology, reproductive and other forms of behavior, and other essential functions.

Increased temperatures also can produce significant indirect effects by decreasing the solubility of oxygen in water. Lowered dissolved oxygen can, of course, cause both increased moribundity and morbidity, depending on the extent of oxygen depletion and the oxygen needs of a particular organism.

A second key change associated with global warming is altered in precipitation patterns. Often discussions focus on changes in annual average precipitation, and the resulting annual streamflow or lake levels. Certainly this effect can be significant, but we must look beyond this one aspect of precipitation patterns. Most lotic (flowing) systems vary significantly in volume throughout the year, as well as from year to year. Aquatic ecosystems are adapted to deal with, even take advantage of, the variation in flows that normally takes place. For instance, the reproductive strategies of most amphibians are attuned to the changes in flows that normally occur during different seasons of the year. However, significant changes in streamflow pattern (average, peak, and low flows; and the timing of peaks and lows) can disrupt reproductive processes and/or other phases of the life cycle of certain organisms, thereby causing substantial changes in the function and composition of aquatic systems.

A second major effect of precipitation changes is changes in patterns of runoff from sources such as agriculture, forestry, construction, transportation systems, industrial sites, and urban development. Changes in runoff can alter the amount and timing of receiving water pollutant loadings such as sediment, nitrogen, phosphorous, metals, oil and grease, and pesticides. The effect of these changes would depend on a variety of factors. For some pollutants, like nutrients (N,P) and bioaccumulative toxic substances, the total loadings over time are usually of greater concern than the concentration at a particular moment. For other pollutants, acute effects are of paramount concern; for them, concentrations are the key concern.

Generally, because pollutants from diffuse sources are discharged to waters during rain events, they are sufficiently diluted by the runoff itself and the increased volume of the receiving water to avoid acute effects; hence, it is chronic effects that are usually of concern. One crucial exception to this rule is the pathogens contained in combined sewer overflows (CSOs). This is a problem found in older cities where the sanitary and storm sewers are joined. During dry weather, the capacity of the sewers is sufficient to handle the volume of waste, coming mostly from residences and commercial establishments, so it all goes to the sewage treatment plant before being released into a receiving water.

When it rains, however, and runoff from the streets goes down into the storm sewers that join with the sanitary sewers, the volume in the system increases dramatically. Depending on the size of the storm, the volume of the combined sanitary waste and storm water may exceed the capacity of the sewers. At this point, relief valves open and untreated sewage is discharged into a water body. This sewage will often have concentrations of bacteria and viruses far in excess of what are considered safe levels, even for very short exposures. If a CSO outfall is located in the vicinity of a beach or other area used for swimming, surfing, wind surfing, or other forms of body-contact water recreation, persons using these areas during or within a day or two of a CSO event can become ill with one of a number of waterborne diseases ranging from gastroenteritis to hepatitis. Health officials may choose to close contaminated areas permanently or temporarily, thereby shifting from a health problem to one of economic impact on tourist-related businesses.

So far, I have only talked about how pollutant loadings and concentrations can be changed as a result of storms increasing runoff and stream flows. At the other end of the spectrum is the effect of climate drying, which results in lowered average and minimum streamflows. Here, the focus is on point-source discharges, rather than nonpoint discharges. Most point-source discharges release pollutants at a fairly continuous rate, though some may release batches periodically. In either case, the pattern of pollutant release is not affected by precipitation patterns. What precipitation does affect is the amount of dilution provided for pollutants in the receiving stream. If as a result of global warming, the flows in a stream are reduced, then the instream concentration of pollutants will tend to increase, assuming discharges remain constant. This, in turn, could exceed water quality standards, with the attendant negative effects on aquatic life and human health.

Another potential effect of having a drier climate is increased use of irrigation in areas so affected. Over time, this can result in increased loadings of salts to waters receiving irrigation drainage flows. For instance, irrigation can result in increased leaching of naturally occurring trace metals such as selenium and boron, which can build up in aquatic systems. This can have very serious effects on wildlife, such as those seen at Kesterson National Wildlife Refuge in California.

On a broader scale, changes in climate may result in major geographical shifts in land-use activities, particularly agriculture and forestry. Clearly, this could result in significant changes in runoff and pollutant loadings to particular water bodies in various regions.

Having contemplated the effects on water bodies that may result from global climate change, it is time to turn to the implications for the regulatory and other programs of EPA and the states, administered under the authority of the Clean Water Act.

First, a simplified explanation of how these programs work starts with those dealing with point sources, such as industrial facilities and municipal sewage treatment plants. Such discharges are regulated under the federally mandated National Pollutant Discharge Elimination System (NPDES) permit program. In most states, NPDES is administered by a state agency, with oversight by EPA. These permits have terms of 5 years, and contain limits on the discharges of various pollutants. The limits are set in one of two ways, through baseline national technology-based performance standards or by establishing end-of-pipe limits based on attaining water quality in the receiving waters. Water-quality-based (WQB) limits are only required where water quality standards are not met through application of technology-based limits.

Climate change should have no effect on technology-based limits, but it could certainly affect water-quality-based limits. Currently, most WQB limits are set by back-calculating end-of-pipe limits from information on the flow of the discharge, the flow of the stream, and the target instream pollutant concentration (that is, the water quality standard). This begs an obvious question: Do you use the average streamflow, or high-flow or low-flow in your calculations? The answer is that most states and EPA use a "design flow" of the low-flow 7Q10. That is the lowest 7-day average flow with an average recurrence interval of once in 10 years. Stream-segment 7Q10s are calculated using historical flow data. If climate change is resulting in more (or less) frequent and/or severe droughts, then clearly regulatory authorities will need to recalculate 7Q10s from time to time, and may need to give more weight to more recent flow data. (This is not an entirely new situation for permitting authorities, as streamflow patterns can also be dramatically changed by development of a watershed.)

Of course, if climate change results in a lower 7Q10 for a receiving water for a discharge, less dilution of the pollutants from the discharge will be available, and more stringent end-of-pipe WQB limits will be required. This could impose significant economic burdens on the dischargers in some instances. One would hope that by the time climate change created this kind of situation, new manufacturing technologies and/or waste-water treatment technologies would make additional pollutant reduction economically and technically feasible; but, in some cases it might not.

An interesting policy dilemma arises if the cost of the additional controls is so great that it forces an industrial facility to close down or a municipal sewage plant to shift to some form of waste-water reuse. This would be beneficial to the stream in terms of a reduced pollutant loading; but, what if most, if not all, of the flow of this stream that had been made much smaller by climate change consisted of wastewater? Total removal of the discharge in such circumstances could exacerbate the effects that had already been caused by climate change. What should we do in such circumstances?

Another potential problem could arrive in dealing with CSOs. First, one must realize one can never totally eliminate overflow and other bypass events in sewage collection and treatment systems. No matter how big you build the pipes or treatment works, there can always occur "the storm of the millennium" that exceeds the design capacity of the system. CSO abatement programs center around reducing the number and intensity of CSO events and/or reducing the amount of pollutants in discharges that do occur. These programs can be quite expensive, especially those aimed at reducing the number of events. It is possible that a community could undertake a multi-year, multi-million-dollar project to increase the storage capacity of the sewer system only to have the benefits of these efforts offset by increases in storm frequency and intensity resulting from climate change. At what point in our planning for climate change do we become sufficiently confident of our predictions regarding changes in precipitation patterns to require incorporation of the expected changes in facility planning for CSOs and other regulated wet-weather flows, like those from separate storm sewers and large animal feedlots?

Obviously, the effect of changing precipitation patterns on loadings from nonpoint sources like agriculture, forestry, and construction would need to be considered. There could also be a change in the efficacy of best management practices (BMPs) aimed at reducing such loadings. This could require updating of models used in developing strategies for managing nonpoint sources.

So, that is what I see as some of the more interesting problems that may arise for water quality programs as a result of global climate change. I might mention that there are other aspects of these programs, such as water quality standards and monitoring activities, where I cannot think of any reason for changes in overall policies or approaches.

I look forward to discussing these questions during the discussion phase of this panel and during the remainder of the conference.

V. Summary, Regional Sensitivity Sessions

SUMMARY OF REGIONAL SENSITIVITY SESSIONS

Joel B. Smith, Deputy Director
Office of Policy and Planning Evaluation
U.S. Environmental Protection Agency

Four breakout sessions were held to review results of regional climate-change impacts studies and to discuss future directions for research on climate-change sensitivities. The breakout sessions were divided by regions--the West, Upper Midwest, Northeast, and Southeast. The following summary of the presentations and discussions in the sessions captures highlights and common conclusions. It is based on the notes and recollections of the rapporteurs.

SENSITIVITIES OF WATER RESOURCES SYSTEMS

Physical Changes

Given all of the uncertainties about the rate and magnitude of climate change, and especially uncertainties about the direction of change in precipitation, one cannot predict whether annual runoff will increase. The following general conclusions about physical impacts can be drawn:

- Snowpacks will melt earlier.
- Potential evapotranspiration will increase in many areas as will evaporation from lakes and reservoirs.
- Water temperatures will increase, although not necessarily as much as air temperatures.
- Low-flow periods in the summer could increase in length and intensity.
- Dissolved oxygen would likely decrease.
- The percentage change in runoff may be greater in arid basins than in humid basins.

Furthermore, higher temperatures likely will increase the hydrologic cycle, which would increase the frequency and intensity of precipitation events. Sea-level rise will increase salinity in estuaries and coastal aquifers, while inundating coastal wetlands. Salinity in estuaries could be further increased by reductions in fresh-water flows.

Demand for Water Supplies

Societal changes such as increased population, economic growth, technological improvement, degree of environmental protection, and changes in water allocation systems probably will have a greater impact on demand for water in many basins than will climate change. It should be noted that significant uncertainty also accompanies these factors, making prediction of baseline changes difficult. Nevertheless, climate change could increase the demand for water for such purposes as irrigation, municipal consumption, pollution control, habitat protection, power plant cooling, and environmental protection.

Implications for Water Resources Systems

Given the uncertainties mentioned above, it is not yet possible to provide precise predictions of the effects of climate change on water resources systems and their various uses. In other words, we are not able to say how much water supply will be available or how much water will be needed at a given year in the future. We are, however, able to draw some conclusions about the relative sensitivities of different uses of water to climate change and likely direction of change in some basins.

Natural ecological systems, such as wetlands and fisheries, may be most vulnerable to climate change. The reason is that their ability to adapt to a relatively rapid change in climate is much more limited than that of mankind. This does not necessarily lead to reductions in aquatic productivity, northern aquatic ecosystems may change but become more abundant. Increases in temperature could decrease dissolved oxygen (DO) levels in lakes and streams, although DO levels may be more sensitive to nutrient loadings. A large reduction in DO levels could dramatically affect native aquatic organisms.

Decreases in water quality could necessitate more advanced treatment for municipal and industrial water pollution control. Cost increases could be significant. The vulnerability of natural ecological systems in many basins may also be greater because societal uses may receive priority over minimum flows for environmental protection.

Societal uses of water for such purposes as drinking, navigation, hydropower, and recreation appear to be more adaptable to climate change. Water managers have been adapting to extreme events and will likely continue to devise ways to cope with changes in droughts, floods, and other climate events. Yet, many existing water allocation schemes limit the flexibility to accommodate climate change.

Nationally, areas with growing populations may be more sensitive to climate change because supplies may become limited anyway. If population growth is combined with poverty, such as in the lower Rio Grande Valley, significant economic dislocation could occur from climate change. Multiple-use water management systems may be quite sensitive as low-flow conditions could lead to reductions in consumptive uses or decreased capability for providing for instream needs. Water managers may face difficult choices between maintaining water quality and ecosystem integrity versus providing for such societal needs as drinking-water supplies, recreation, navigation, flood protection, and other uses. Systems with large storage capacity may provide more flexibility to managers to adapt to climate change.

Among the other likely impacts are that earlier snowmelt in the West would likely increase winter flooding and reduce water supply reliability. On the other hand, hydropower production could increase some areas in the region. The reliability of water supplies of some coastal cities such as New York would be reduced by sea-level rise, which will increase salinity in estuaries and aquifers. Changes in runoff could further affect these coastal areas. Among the specific water uses affected by climate change are power plants, which need water to be below certain temperatures to provide cooling.

Future Research Directions

Each session had discussions about the methodologies for determining sensitivities and issues for analysis. No consensus emerged about a "right way" to conduct sensitivity studies. The use of mesoscale climate models "nested" within general circulation models was raised in several sessions. There will likely still be uncertainties with the use of these models. Other approaches to test sensitivity to climate change include arbitrary changes in variables such as temperature and precipitation and the use of historical data, such as the worst drought. A number of studies have incorporated projected increases in demand for water supplies.

Sensitivities to climate change can be identified by analyzing systems that are already sensitive to known variability. Another approach to identifying thresholds should include ecological impacts. Identification and analysis of sensitivities should try to differentiate between types of systems (e.g., upstream versus downstream, watershed type, or vegetation) and their relative sensitivities. Sensitivities should not simply address changes in events--floods and droughts--and need information on how they may change and how their system would be affected. Very few studies have addressed changes in variability and extreme events. This area needs further methodological development. Future studies should also examine impacts on the supply of and demand for groundwater.

Finally, climate-change impacts should be put into context. We should try to distinguish between significant and insignificant impacts. Economic valuation of impacts is one way to identify the relative value to society of climate-change effects.

VI. Panel Discussion, Issues for Water Management

ISSUES FOR WATER MANAGEMENT

Harry E. Schwarz
Professor of Environment, Technology, and Society and Geography
Clark University

The panel was moderated by Professor Harry Schwarz of Clark University. It consisted of J. Darrell Bakken (Indianapolis Water Company), Peter Gleick (Pacific Institute), James R. Hanchey (U.S. Army Corps of Engineers), Gerald Hansler (Delaware River Basin Commission), Terry Lynott (U.S. Bureau of Reclamation), Peter Rogers (Harvard University), and Robert Varady (University of Arizona). In opening, the moderator asked the panel members to consider three questions and to present their views on climate change and water resources management in general. The three questions posed were as follows:

1. Do you believe climate change will happen and do you believe that knowledge of such change is important to you?

2. Assuming an affirmative answer to the first question, what information would you want to be supplied by the scientists, and what proof would you require from them for you to believe them?

3. Accepting the present state of knowledge, the acknowledged range of uncertainties, and the fact that climate change is on the political agenda, what steps would you undertake to include consideration of climate change in your planning and action?

Almost all panel members agreed in responding to question 1. Answers such as "climate change is more definite than heaven or hell" set the tone. Mr. Bakken observed that while he agreed that climate change is likely to occur, it is less important than other considerations in water management.

As to the second question, everyone agreed that more information is needed and such information would be important to the water manager. Members, however, made a number of important points. Dr. Rogers stated that better explanation by the scientists of what is and what is not known would be valuable, and that proof in the usual sense cannot be given for climate change. There is no controlled experiment that can tell us that some specific thing will occur. We are all inside of a sort of global experiment. Mr. Bakken reminded us that, as a utility, his organization has to go before regulatory bodies that require fixed and measurable quantities to make their decisions. Thus, in his view, a strong consensus is needed on what might happen, rather than the broad uncertainties based on several models producing different outputs. Mr. Hansler told of a major item of information now available in his area. He described a study by the U.S. Geological Survey that analyzed the impacts of climate change on the water resources, flow and precipitation, sea-level rise, and temperature in the Delaware River basin. The study projected a rise in temperature, a decrease in streamflow, and a rise in sea level, but also stated that the present variation in precipitation and runoff from year to year is a more important factor to be considered in water management than changes due to climate change caused by the greenhouse effect. Dr. Gleick made the point that climate change presents a risk problem; risk in the classic sense of probability of an event times the consequences of the event. This risk will vary on a regional as well as a sectoral basis, but is likely very great. A low standard of proof should, in his opinion, be needed to get water managers to think about the problem and include it in their planning.

In answer to the third question, Dr. Rogers stated that while he would recommend more research he would like to see some shift in the focus of the research from modeling to basic hydrology and the effect of climate changes on such things as moisture deficiencies. He further called for planning and planning methodology to be put back on the national agenda. Speaking for his water utility, Mr. Bakken felt that its continuously updated multi-year plans have served the company well and will continue to do so under climate change. Mr. Hanchey added his voice to a call for planning. He stated that we have moved away from comprehensive multi-objective basin-oriented planning toward narrow-focused project-oriented planning that he considered totally inappropriate to the kinds of issues and uncertainty we face with climate change. In his view, EPA is the only agency that is planning in a more comprehensive manner, albeit on the limited focus of water quality. To Mr. Hansler the rise in sea level has the most immediate impact on his area, and his agency will look at this problem. He also raised the question of who would pay for costs arising from global warming. Will it be the federal government or the states and local communities? Mr. Varady took issue with question 3. In his view, climate change does not have a strong place on the political agenda. Dr. Gleick pointed to the inherent robustness of our water resources systems and our ability to change their operation to fit changing conditions, a flexibility that is not being used to its full advantage.

The panel made a number of other significant points:

- The importance of planning was repeated. While a 5-year outlook was considered reasonable for dealing with a public utilities commission, longer planning horizons such as 25 years were thought appropriate.

- There is great need to monitor climate, both regional and global, in a formal and well-organized manner. Sea-level rise should be better defined to account for both rise of the sea level and dropping of the Continental Shelf.

- Climate change, while barely on the political agenda, is not even on the professional one. Among Corps of Engineers staff and others who deal on a daily basis with planning and design of projects, there is a very low level of knowledge about climate change and a great deal of skepticism.

- While past projects usually were designed for rare conditions, either floods or droughts, today's projects are smaller and are designed with less margin for rare events. Further, changes in the values the public perceives from water development operating rules are changed to, for instance, provide more recreational values. Thus, systems today are more stressed and likely less able to adjust to additional stress from climate change.

- People are not willing to make drastic changes to prepare for possible climate change. And, if so, are we operating our systems in the best manner for the now-known variables, and could we operate better and so adjust incrementally to climate changes?

- The system on the Delaware River that now supplies users in New York, New Jersey, and Pennsylvania is able to withstand the equivalent to the maximum drought of record. Greater droughts and sea-level changes due to climate change could still be sustained if a water intake and a canal were to be constructed from a point above the rocks at Trenton. The question is who would pay for such a project?

- Water managers are subject to a wide range of pressures. Many of these are fiscal; others emanate from various constituencies. It is therefore important that information from this conference and from scientific research on climate change be widely disseminated. The Bureau of Reclamation through its publications and its research support has begun such an effort.

- The water industry is under pressure to comply with a number of new legal requirements, such as the Safe Water Drinking Act. To comply is expensive, and so little is left over to consider climate change. The American Water Works Association has never discussed climate change but it is necessary to do so now.

- If responses to climate change are to be undertaken, and if they are to succeed, they must have broad popular support. When the present models still meet with skepticism by decision-makers, how will they convince the population at large? If bottom-up responses are to emerge, they have to be stimulated by creative new activities such as those that have successfully brought about other environmental actions.

- Water use in the United States has been decreasing both totally and on a per capita basis. Conservation is one of the tools in adapting to climate change.

- Some very rare events have enormous impacts. The Oakland fire and the resulting devastation was caused by the simultaneous occurrence of a number of meteorological, physical, and societal factors. One of the problems was the lack of a prepared plan to handle such a calamity. So with climate change, we can take steps, many of which would incur little cost. We buy insurance for events we do not expect to occur; why not consider steps related to climate change as a form of insurance? Furthermore, there are many things we should do for other good reasons that would help us to contain or adapt to climate change, from energy efficiency to water conservation.

- Much was made of the inconsistency in the results of the various GCMs. If all the models resulted in the same answers, they would not necessarily be correct.

- A basin-wide approach to the study of impact of climate change should be strongly urged. A basin is a good integrator of many parameters important in water management decisions.

- Climate change is not a scientific problem. In spite of the uncertainties, we know enough to act. It is a problem of political will and it is likely that nothing will be done.

BROADENING OUR HORIZONS AND RECOGNIZING THE ROLE OF PUBLIC PARTICIPATION: SOME OBSERVATIONS ON THE FIRST NATIONAL CONFERENCE ON CLIMATE CHANGE AND WATER RESOURCES MANAGEMENT

Robert G. Varady, Associate Director
The Udall Center for Studies in Public Policy
University of Arizona
Tucson, Arizona

In contemplating the subject at hand, I'm reminded of the phrase coined by the late comedian and social observer, Gilda Radner: "It's always something." So now it's climate change.

We've heard the familiar arguments about climate change, its likelihood, its magnitude, its potential impact. The preponderance of evidence presented at these meetings suggests that we *can* look forward to a trend of higher temperatures, largely due to current human practices.

Some people here and elsewhere have asked, "So what?" But a more useful question is, "Now what?" The literature agrees that three types of responses exist: prevent warming, adapt to it, or do nothing. One of the problems in determining appropriate responses is that policy-makers and implementers seize upon the uncertainty factor and claim that anything less than total certainty is insufficient. But at the first of our sessions, in reply to a pointed question from the audience, we heard the director of California's Department of Water Resources admit that even if he knew with absolute certainty that climate change *will* occur, "no single thing would be done differently." As David Rind of NASA added yesterday, after hearing his presentation of the results of his modeling, a group of California water resources planners characterized climate change as "just one more problem." Or, as my co-panelist, Darrell Bakken of the Indianapolis Water Authority put it a few moments ago, "just another eight hours of homework, assigned by a professor whose own course is the most important."

In other words, Peter Rogers probably was correct on the first day when he cynically noted that even if everything were known and if planners had access to this information, not much would change.

Indeed, we've grown hardened to such cynicism, but let me raise the stakes. If this observation is valid in one of the world's richest areas--the United States and California in particular--how much more true it must be elsewhere! Dr. W.W. Kellogg acknowledged this in his talk, but his point was that poorer countries lack the resources to take corrective measures. I would go further. There are dozens of nations like Mauritania, Chad, Burma, Guatemala, and Albania (to name just a few) where I can't even conceive that the issue of climate change has a place on the political agenda.

As we heard from several speakers, this observation is pregnant with ethical implications such as who bears responsibility for causing climate changes, what are the costs of the effects, who will pay, and are the likely solutions equitable? Unlike Mr. Bakken, who deplored the expenditure of scarce EPA funds on studies of African river basins (those funds would be better spent on the Wabash, he stated), I commend that agency for having the foresight to at least study the potential impact of *our* actions on *other* parts of the world.

But let me return to the question of action versus inaction here in our own hemisphere. If U.S. decision-makers and administrators face difficulties in responding to the kinds of scenarios that have been proposed, imagine how much more complex such responses must be in trans-border regions. During the 2 days of discussions I heard virtually no mention of our borders with Mexico and Canada. It was as if the climate processes examined behaved nicely within national frontiers. But we tend to forget how much more difficult it is to confront problems--physical and social--that defy national sovereignty.

I'd like to offer just one example. For the past 2 years the Udall Center at the University of Arizona has undertaken a project, funded by the Ford Foundation, whose aim is to understand how water resources are managed in a trans-border setting. In particular, we have been looking at the twin communities of Nogales, Arizona, and Nogales, Sonora. To do this we have developed a comprehensive GIS (geographic information system) that exhibits the typical characteristics of water supply, sewage removal, and demography. But we have added another mappable feature: the overlapping jurisdictional authorities that have a role in water management decisions.

Both in the United States and in Mexico, a large array of agencies, entities, and instruments come into play. In the United States, at the binational level, there are the International Boundary and Water Commission (IBWC), the 1983 La Paz Agreement, and the incipient Integrated Border Environment Plan. Federally, various agencies pursue differing and sometimes conflicting mandates that relate to water: EPA, Bureau of Land Management, Bureau of Reclamation, Department of Agriculture, Forest Service, National Park Service, and Corps of Engineers. At the state level, water decision-makers include the Departments of Environmental Quality, Water Resources, and Agriculture, as well as the Active Management Area defined by the Arizona Groundwater Management Act. Closer to home the county Department of Health and Board of Supervisors, and the municipal water district, sanitation district, and private water companies complete the picture.

The situation is comparable in Mexico, where a strong federal system of government includes counterparts to the IBWC (CILA), EPA (SEDUE), and the Department of Agriculture (SARH), as well as a national water commission (CNA). The state of Sonora and the municipality of Nogales also maintain local administrative authority over certain services and functions.

In other words, decision-making and implementation, which are in any event more complicated and multi-layered than one might think, are even more so in the trans-border setting.

Now, one of the impressions I have been left with from these proceedings was best conveyed by EPA Deputy Assistant Administrator Dan Esty during his luncheon talk yesterday. If he were here, Mr. Esty probably wouldn't remember his remark because it was a slip of the tongue. Referring to intended actions, he said, "participatory ... errr ... anticipatory." A telling slip, because it suggests that intended actions should be "top-down."

But as most of you are aware we are passing through a period of sustained disenchantment with and mistrust of government. Policies often fail precisely because they have *not* been designed in a participatory fashion.

In Nogales we have observed that when things get done in the realm of water management, it is usually because of local actions and initiatives. The most effective strategies we have witnessed have been grassroots-initiated--by NGOs, citizens' interest groups, environmental organizations, or residents' associations, often working through informal networks, and often in spite of inertia on the part of more distant entities.

In climate change, too, if responses are to be undertaken, and if they are to succeed, they must derive broad popular support. There has been considerable skepticism about the ability of arcane technical models to convince decision-makers. These models are even less likely to convince the population at large. If any "bottom-up" responses are to emerge, they will have to be stimulated by creative, new actions such as those that have been used successfully to remediate other environmental problems.

In sum, it is useful to convince decision-makers that climate change matters, but someone needs to convince the public.

VII. Biographies of Speakers

J. DARRELL BAKKEN

Mr. Bakken is Vice President and Director of Engineering, Indianapolis Water Company, Indianapolis, Indiana. He is a hands-on expert in the management of municipal water. A Diplomate American Academy of Environmental Engineers, he earned his M.S. in Civil Engineering at the University of Minnesota. He is a member of the American Water Works Association (Fuller Award, 1966, and Life Member, 1983); Water Pollution Control Federation; National Society of Professional Engineers; American Society of Civil Engineers; and Dean's Industrial Advisory Committee, Purdue School of Science, IUPUI.

THOMAS M. BRUNS

Mr. Bruns is Principal Hydrologist with the Indianapolis Water Company, with primary responsibilities in the areas of water resources development and land management. He joined IWC in 1989 after a 15-year career with the Indiana Department of Natural Resources, where he served as Deputy Director from 1968 to 1989. He holds a B.S. in Earth Sciences from Ball State University and an M.A. in Geology from Indiana University. He is a member of AWWA, AIPG, WPCF, and NWWA, and has presented several papers on water resources management and groundwater development issues.

STEWART J. COHEN, PH.D.

Dr. Cohen is an Impacts Climatologist with the Canadian Climate Centre, Atmospheric Environment Service, Environment Canada, Metropolitan Toronto, Ontario. He received university training in geography from McGill University, the University of Alberta, and the University of Illinois, where he obtained a Ph.D. in 1981. Dr. Cohen has published several works on regional impacts in the Great Lakes and Saskatchewan River watersheds, and is currently organizing a major interdisciplinary study of the Mackenzie basin. He has served as an external reviewer and advisor to the U.S. Environmental Protection Agency and to the International Joint Commission's Water Levels Reference Study of the Great Lakes.

WILLIAM S. COOTER, PH.D.

Dr. Cooter is a Research Environmental Scientist, Center for Environmental Analysis, Research Triangle Institute. He works in synthesizing monitoring data from individual water bodies into assessment information to support watershed and basin-level planning and management decision-making. Dr. Cooter's expertise includes a background in both water quality modeling and economic climatology.

DARRYL W. DAVIS

As Director, U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, California, Mr. Davis heads a staff of 30 engineers and computer scientists performing research, training, and technical assistance in hydrologic engineering and water resources planning support of Corps offices nationwide. The broad range of technical subjects and applications within the scope of HEC activities includes river hydraulics, watershed hydrology, reservoir systems, erosion and sediment transport, hydrologic statistics, analytic planning, groundwater, and water quality. The water resources applications areas include flood control and damage reduction, navigation, hydroelectric power, streambank erosion, water supply and quality management, and other ancillary purposes.

JOHN A. DRACUP, PH.D.

Dr. Dracup is a Professor of Engineering and Applied Science in the Civil Engineering Department, University of California, Los Angeles. He holds a B.S. in Civil Engineering from the University of Washington an M.S. in Civil Engineering from the Massachusetts Institute of Technology, and a Ph.D. in Civil Engineering from the University of California at Berkeley. He has been a member of the UCLA engineering faculty since 1965 and formerly was Chairman of the Engineering Systems Department. His professional interests and expertise are in the fields of hydrology and water resources systems engineering. Recent research work has involved the statistical analysis of hydrologic droughts, the modeling of groundwater systems, the analysis of flash floods in ungauged watersheds, the optimization of energy use in urban water districts, the hydrologic analysis of alpine watersheds under acid deposition stress, and the impact of global warming on hydrologic and water resources systems.

CHARLES T. DUMARS

Mr. DuMars is Professor of Law, University of New Mexico School of Law, Albuquerque, New Mexico. His many publications include the following:

- "Conjunctive Management of Ground Water and Surface Water: New Mexico Caselaw and Policy Issues," in *Groundwater, the Unseen Crisis* (University of Texas Press, 1985).
- "Federal/State Relations in Theory and Practice: A Sovereignty Mismatch," in *Western Water Law in Transition* (University of Colorado School of Law, 1985).
- "Water Rights and Market Transfers," Chapter 19, Part IV, in *Water Scarcity, Impacts on Western Agriculture* (University of California at Davis Press, 1984).
- "Legal Parameters of a State Controlled Water Market," in Seminar, Water Policy Management Options, Select Committee on Water Markets, State of Montana (Montana Department of Natural Resources, 1984).

STEPHEN ESTES-SMARGIASSI

Mr. Estes-Smargiassi is Program Manager, Long Range Water Supply Planning, Massachusetts Water Resources Authority. He is an engineer (B.S. in Civil Engineering from MIT) and a planner (Master of City and Regional Planning from Harvard University). His current responsibilities at the Massachusetts Water Resources Authority include supply and demand planning and program evaluation, watershed protection, and overall water system master planning. He oversaw the successful implementation of a comprehensive demand-side approach to supply planning at the MWRA over the past 4 years that has resulted in 15 percent reductions in demand and brought demand and supply into balance for the first time in over 20 years. As a part of his responsibilities, he is currently managing an evaluation of the impacts of climate change on the system's safe yield. Based on these impacts he expects to recommend to the Board of Directors any necessary changes in operating policy or planning assumptions to maintain a reliable supply into the next century.

MYRON B. FIERING, PH.D.

Dr. Fiering has been at Harvard's Division of Applied Sciences since the start of the Harvard Water Program in 1957. His principal interests include the proper role and assessment of statistical models for decision-making in water resources, including the option of not using them at all because of statistical and phenomenological imprecision.

KENNETH D. FREDERICK, PH.D.

Dr. Frederick received a Ph.D. in Economics from the Massachusetts Institute of Technology, and is a Senior Fellow at Resources for the Future. He has written widely on the economic, environmental, and institutional aspects of water resources use and management as well as on the possible implications of climate change for the use and supply of water.

PETER H. GLEICK, PH.D.

Dr. Gleick is a Senior Associate of the Pacific Institute for Studies in Development, Environment, and Security in Berkeley, California. He received his M.S. and Ph.D. from the Energy and Resources Group at the University of California at Berkeley. He is on the Climate and Water Panel of the American Association for the Advancement of Science, and has published widely on the subjects of climate change, water resources, and environmental policy.

JAMES R. HANCHEY

Mr. Hanchey is the Director of Planning for the Lower Mississippi Valley Division/Mississippi River Commission, U.S. Army Corps of Engineers, and a member of the federal government's Senior Executive Service. In addition to a B.S. in Civil Engineering from the University of Southwestern Louisiana, Mr. Hanchey received an M.S. in Civil Engineering from Tulane University. He has also completed 2 years of graduate study in Water Resources Engineering at Stanford University. Mr. Hanchey is a registered professional engineer in the state of Louisiana. The Lower Mississippi Valley Division (LMVD) is responsible for Corps water resources programs in a 156,000-square-mile area of the Mississippi River Valley. District offices are in Memphis, New Orleans, St. Louis, and Vicksburg. The presidentially appointed Mississippi River Commission (MRC) is responsible for the comprehensive Mississippi River and Tributaries flood control and navigation project.

GERALD M. HANSLER

Since October 1977, Mr. Hansler has been Chief Executive Officer of the interstate-federal Delaware River Basin Commission (DRBC), the instrumentality established in 1961 when the states of New Jersey, New York, and Delaware; the Commonwealth of Pennsylvania; and the United States enacted the Delaware River Basin Compact. The five-member commission includes the governors of the four states and the Secretary of the Interior. The DRBC is responsible for promoting interstate comity in water and related land resources planning, management, development and protection for the 13,000-square-mile basin region. Mr. Hansler supervises a staff of about 50, mostly professional and technical specialists in fields of water supply allocation, flood protection, water quality improvement, fisheries enhancement, water-based recreation, and environmental protection including consideration of toxic wastes.

GARY HESTER

Mr. Hester has been a Flood and Water Supply Forecaster for the California Department of Water Resources since 1983 and has been Chief Forecaster since 1988. He supervises the snowmelt runoff forecasts published in "Water Conditions in California" and the state team that issues flood bulletins in cooperation with the National Weather Service. He received a B.S. in Environmental Engineering from Humboldt State University and is a member of the American Society of Civil Engineers.

BENJAMIN F. HOBBS, PH.D.

Dr. Hobbs earned a B.S. from South Dakota State University, an M.S. in Resources Management and Policy from the State University of New York at Syracuse, and a Ph.D. in Environmental Systems Engineering from Cornell University. He is Associate Professor of Systems Engineering and Civil Engineering at Case Western Reserve University, Cleveland, Ohio. He is presently on sabbatical leave at the Department of Civil Engineering at the University of Washington, Seattle. Dr. Hobbs' current research areas include inclusion of risk and multiple objectives in electric utility planning, management of Great Lakes levels under climate uncertainty, and compliance planning for electric utilities under the Clean Air Act of 1991.

HENRY D. JACOBY, PH.D.

Dr. Jacoby is William F. Pounds Professor of Management in the MIT Sloan School of Management. He studied mechanical engineering at the University of Texas at Austin and earned a Ph.D. in Economics from Harvard University. He is an applied economist studying issues of policy and planning in the areas of energy, natural resources, and the environment. Dr. Jacoby has served as Director of the Harvard Water Program and the Harvard Environmental Systems Program (1965-1969), Director of the MIT C[illegible] for Energy Policy Research (1978-1980), and Associate Director of the MIT Energy Laboratory (1980-1983). At present he is Co-Director of the Joint Program on the Science and Policy of Global Change, which is a shared activity of the MIT Center for Global Change Science and the MIT Center for Energy Policy Research.

WILLIAM W. KELLOGG, PH.D.

Dr. Kellogg joined the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, in 1964 and served for nearly 10 years as Director of its Laboratory of Atmospheric Sciences. He then became a Senior Scientist until his retirement from NCAR in February 1987. Before joining NCAR, he was head of the Planetary Sciences Department of the Rand Corporation in Santa Monica, California, where he worked for 17 years. Dr. Kellogg obtained a B.A. in Physics at Yale University and an M.A. and Ph.D. in Meteorology at UCLA.

DAVID N. KENNEDY

Mr. Kennedy has been Director of the California Department of Water Resources since June 1983. Before his appointment, he was Assistant General Manager of the Metropolitan Water District of Southern California. He received B.S. and M.S. degrees in Civil Engineering from the University of California at Berkeley. Mr. Kennedy is a member of various professional organizations and is active in the Western States Water Council.

PAUL H. KIRSHEN, PH.D.

Dr. Kirshen is a water resources consultant with over 20 years of experience in water resources planning and engineering. Recent experience includes research on the use of general circulation models (GCMs) and local effects models to study the potential impacts of possible climate change on flood management in south Florida, and on the implementation of conceptual hydrologic runoff models for several watersheds in the United States. He has served as a consultant to the New England River Basins Commission on a variety of water resources issues important to Massachusetts and New England. Dr. Kirshen has a B.S. in Engineering from Brown University and M.S. and Ph.D. degrees in Civil Engineering (Water Resources) from MIT.

VIT KLEMEŠ, PH.D.

Dr. Klemeš received a Civil Engineering degree and a Ph.D. in Hydrology and Water Resources from the Technical Universities in Brno and Bratislava, Czechoslovakia, respectively. He worked in the planning, design, and assessment of water resources systems with a Czech government agency for 8 years and then joined the Hydrology and Hydraulics Research Institute of the Slovak Academy of Sciences. In 1966 Dr. Klemeš moved to Canada, where he taught at the University of Toronto. From 1972 to 1990 he worked at the National Hydrology Research Institute of the Federal Department of the Environment in Ottawa and Sask where he was Chief Scientist for the last 10 years. During that period, he was Visiting Professor at lifornia Institute of Technology, ETH Zurick, and Monash University, and from 1987 to 1991 was Pres of the International Association of Hydrological Sciences.

JOSEPH F. KOONCE, PH.D.

Dr. Koonce has been on the faculty of Case Western Reserve University since 1973. He currently has a joint appointment in the Departments of Biology and Systems Engineering. Dr. Koonce obtained his A.B. from Dartmouth College in 1967 and his Ph.D. in Zoology from the University of Wisconsin at Madison in 1972. For the past 10 years, his research has focused on the interface between ecological theory and management of renewable resources.

MICHAEL R. KROUSE

Mr. Krouse is Chief, Research and Technical Analysis Division, U.S. Army Corps of Engineers Institute for Water Resources. He currently develops, manages, and executes Corps civil works research and development and training programs in planning methodologies, water supply planning and conservation, risk analysis, and environmental valuation. He also manages a substantive technical assistance program related to water resources planning. In the past, he has planned and conducted specific research; Corps-wide training and policy analysis related to planning guidance; and cost-sharing and evaluation techniques for a range of water resources planning and management issues including coastal protection, water supply, water quality, and flood control. He also has conducted economic analyses for River Basin Comprehensive Studies, and developed forecasting methods and basin-wide projections of flood control and navigation needs.

DENNIS P. LETTENMAIER, PH.D.

Dr. Lettenmaier is a Professor of Civil Engineering at the University of Washington. His area of specialization is surface water hydrology. Past research interests have included water quality monitoring, network design, statistical hydrology, and water resources management. His recent research interests have been in the area of large-scale land surface hydrologic-atmospheric interactions and hydrologic sensitivities to climate change. He was the Lead Investigator in the Sacramento/San Joaquin Water Resources Study for the 1988 Environmental Protection Agency report to Congress on the Potential Effects of Global Climate Change.

TERRY P. LYNOTT

Mr. Lynott has had a 28-year career with the Bureau of Reclamation and the Department of the Interior. In his present position as Director of Program Services, he oversees the policy and program direction for Reclamation's General Investigations, Loans, and Operation and Maintenance programs. Mr. Lynott's organization spans a variety of disciplines that address earth sciences, engineering, environmental issues, economics, and social impacts. The office uses a streamlined matrix management process to reform policy and technical implementation work for Reclamation's regional offices and other clients. He has been instrumental in the reorientation of Reclamation's mission and its reorganization. Prior to assuming his current position, Mr. Lynott served as Reclamation's Assistant Commissioner for Planning and Operations in Washington, D.C. In that capacity, he was responsible for planning, power operation, and maintenance of Reclamation project facilities, environmental affairs, youth programs, and the activities of the Colorado River Water Quality Office.

LAWRENCE J. MACDONNELL, PH.D.

Dr. MacDonnell is Director of the Natural Resources Law Center at the University of Colorado. He holds a J.D. from the University of Denver College of Law and a Ph.D. from the Colorado School of Mines. His research in recent years has focused largely on water issues.

DAVID C. MAJOR

Mr. Major, an economist and planner, is the author of three books on water resources. He has taught at Harvard, MIT, and Clark and has been a senior planner for the New York City water supply system. He is now the Social Science Research Council's program director for global environmental change.

BARBARA MILLER, PH.D.

Dr. Miller is a Senior Civil Engineer at the Tennessee Valley Authority's Engineering Laboratory. She manages the Reservoir System Analysis Group at the laboratory, which is responsible for the continued development and application of an operational planning model used to simulate reservoir operations and hydropower production at 42 major reservoirs in the TVA system. This model is used for hydropower scheduling, as well as to evaluate proposed changes in reservoir operations.

KATHLEEN A. MILLER, PH.D.

Dr. Miller is an economist with the Environmental and Societal Impacts Group at the National Center for Atmospheric Research. She holds a Ph.D. from the University of Washington. Much of her research has focused on aspects of the interaction between climate and water institutions. She has also studied the socioeconomic impacts of climatic variability, including the effects of severe freezes on Florida's citrus industry and the effects of climate variations on the Pacific Northwest salmon fisheries. Her other interests include the economic management of climate uncertainty.

WILLIAM J. MILLER, PH.D.

Dr. Miller specializes in water resources, water supply, and water quality problems as a consulting engineer serving a variety of public agencies and private sector interests. He at present is advising the Turlock Irrigation District regarding provision of treated surface water to communities in its service area. He also is consultant to the State Water Contractors (most of the entities that buy water from the California State Water Project) for the Bay-Delta hearings before the State Water Resources Control Board. This has involved planning for and coordinating the testimony of the State Water Contractors in cooperation with the State Department of Water Resources, the Bureau of Reclamation, and the Central Valley Project Contractors. In the past, Dr. Miller has served as consultant to the California Urban Water Agencies and the California Farm Water Coalition for the Three-Way Water Agreement Process, whereby environmental, agricultural, and urban water leaders are working toward a broad agreement on California water policy.

KENNETH H. MURDOCK

Mr. Murdock is the Director of the Water Resources Support Center at Fort Belvoir, Virginia, where he oversees the work of the following National Centers of Expertise of the U.S. Army Corps of Engineers: the Hydrologic Engineering Center, Davis, California; the Institute for Water Resources, Fort Belvoir, Virginia; the Navigation Data Center, Fort Belvoir (including the Waterborne Commerce Statistics Center, New Orleans, Louisiana); and the Washington Level Review Center, Fort Belvoir, Virginia. Mr. Murdock earned a B.S. and M.S. degrees in Civil Engineering from the Catholic University of America in Washington, D.C.

LINDA L. NASH

Ms. Nash is a Senior Associate of the Pacific Institute for Studies in Development, Environment, and Security in Berkeley, California. Her current research is in the areas of water resources management and water quality. She is a member of the ASCE Committee on Climate and Weather Change. She holds an M.S. in Energy and Resources from the University of California at Berkeley and a B.S. in Civil Engineering from Stanford.

WILLIAM PAINTER

Mr. Painter studied biological sciences at Duke and the University of Michigan. He has 20 years of experience in environmental policy, with a focus on water issues, including both water quality and quantity. He currently is Chief of the Water Policy Branch in the Office of Policy Analysis at the Environmental Protection Agency. The branch deals with a wide array of policy matters, including controls on industrial and municipal waste-water discharges; management of pollution due to runoff from urban areas, industrial facilities, farmlands, and forestry operations; protection and restoration of aquatic habitats; and relationships between water quantity and surface groundwaters.

FRANK H. QUINN, PH.D.

Dr. Quinn is the Head, Physical Sciences Division of the Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration (NOAA), Ann Arbor, Michigan. The division conducts research on physical processes of the Great Lakes and their basin including hydrology, hydraulics, waves, circulation, ice, and thermal structure. Dr. Quinn received B.S. and M.S. degrees in Civil Engineering from Wayne State University, and a Ph.D. in Civil Engineering from the University of Michigan. His specialty is the hydraulics and hydrology of large lake systems.

STEVEN L. RHODES, PH.D.

Dr. Rhodes is a political scientist with the Environmental and Societal Impacts Group at the National Center for Atmospheric Research. He earned a Ph.D. from the University of Colorado in 1980. He has written about environmental issues such as acid rain and other atmospheric pollution, renewable energy technology policy, the use of climate-related information in resource management, decertification, and cleanup of contaminated federal facilities in the United States.

WILLIAM E. RIEBSAME, PH.D.

Dr. Riebsame is Director of the Natural Hazards Research and Applications Information Center at the University of Colorado. The center was founded in 1976 as a national information clearinghouse on the social and economic aspects of natural hazards and their mitigation. It provides information, referral, and library services to the U.S. hazards community. Dr. Riebsame received a Ph.D. in Geography from Clark University in 1981, where he studied farmers' responses to drought in the U.S. Great Plains. After teaching at the University of Wyoming, he became Director of the Natural Hazards Center in 1983. His expertise is in the interaction of people and environment, especially as relates to how resource managers make choices; impacts of weather and climate hazards; and the social dimensions of large-scale environmental change. Recent research includes studies of the effects of climate change on water resources management in the United States and several international river basins, trends in hazard vulnerability in the United States, and the sustainability of resource management in semi-arid regions.

DAVID RIND, PH.D.

Dr. Rind is a climate modeler for the NASA Goddard Institute for Space Studies (GISS). He is responsible for both model development and model applications, and has used the GISS model for studies of both past and future climates, with emphasis on climate and hydrologic sensitivity. Dr. Rind received his Ph.D. from Columbia University in 1976. He has been associated with GISS since 1978, and is also an adjunct professor at Columbia University. He is a member of various governmental and international committees investigating the likelihood of global change.

PETER PHILIPS ROGERS, PH.D.

Dr. Rogers is Gordon McKay Professor of Environmental Engineering and Professor of City and Regional Planning at Harvard University. He is also a Member of the Center for Population Studies at Harvard, where he received his Ph.D. in 1966. Dr. Rogers has done research on improved methods for managing natural resources and the environment, with emphasis on the use of analytic optimizing methods to incorporate both the natural phenomena and the engineering controls; and on development of mesoscale models of resource management that relate directly to macro-economic parameters.

NORMAN J. ROSENBERG, PH.D.

Dr. Rosenberg is Senior Fellow and Director of the Climate Resources Program, Energy and Natural Resources Division, at Resources for the Future, Washington, D.C. He received a B.S. from Michigan State University, an M.S. from Oklahoma State University, and a Ph.D. from Rutgers University. His areas of expertise include agricultural climatology, agricultural meteorology, and agricultural engineering.

JOHN C. SCHAAKE, JR., PH.D.

Dr. Schaake is Senior Scientist, Office of Hydrology, National Weather Service, National Oceanic and Atmospheric Administration. He earned his Ph.D. at Johns Hopkins University in Environmental Engineering and Water Resources, and was a Post-Doctoral Fellow in the Harvard Water Program. His activities relating to climate and water resources include serving on the AAAS Panel on Climate and U.S. Water Resources. Related work included writing a chapter in a published book dealing with sensitivity of water resources to climate change. He recently chaired a science panel for the Global Water and Energy Cycle Experiment (GEWEX) Continental-Scale International Project of the World Climate Research program; and served as World Meteorological Organization (WMO) Rapporteur on the subject of Hydrologic Models for Use in Climate Studies. Dr. Schaake developed a simple orgraphic precipitation model to analyze spatial distribution of precipitation in the western United States for input to hydrologic models and to assess information content of precipitation and snow measurement networks. This work was done in cooperation with several federal agencies including the Bureau of Reclamation, Soil Conservation Service, U.S. Geological Survey, and Department of Energy.

KYLE E. SCHILLING

Mr. Schilling is Director of the Institute for Water Resources, U.S. Army Corps of Engineers. He manages a diverse and rapidly responsive program of studies, and research relating to current issues in the changing national water resources environment. His experience centers on comprehensive resources planning, water supply, and water conservation planning. He directed the staff efforts of the 1977 White House Drought Study Group and the 1980 President's Intergovernmental Water Policy Task Force, Subcommittee on Urban Water Supply. He was also the principal author of the National Water Resources Infrastructure Needs Study, completed in 1987 for the National Council on Public Works Improvement. He recently organized and directed a NATO Advanced Research workshop on Urban Water Infrastructure.

JURGEN SCHMANDT, PH.D.

Dr. Schmandt is Director of the Center for Global Studies (CGS) at the Houston Advanced Research Center, a Texas research consortium. CGS focuses on global growth issues (population, resources, and environment) and their social, economic, and political implications. In addition to directing CGS, Dr. Schmandt is a Professor of Public Affairs with the Lyndon B. Johnson School of Public Affairs at the University of Texas at Austin. Educated at the University of Bonn, he has served on the Texas Governor's Science and Technology Council, and has chaired an advisory committee on international programs for the National Science Foundation. He also spent a year as a Senior Research Fellow with the U.S. Environmental Protection Agency in Washington, D.C. Before joining the faculty of the LBJ School, he held positions with Harvard University's Program on Technology and Society and with the Organization for Economic Cooperation and Development (OECD) in Paris, France.

RONALD J. SCHUSTER

Mr. Schuster is Manager of the Bureau of Reclamation's Global Climate Change Response Program. He has been with the Bureau of Reclamation for 16 years working in the areas of water project design, planning, hydrology, and river systems management. Mr. Schuster oversees and coordinates the overall program, which is designed to study the potential impacts of climate change on water resources in the 17 western states and to develop responses and strategies to deal with those impacts. The program consists of approximately 15 technical research projects.

HARRY E. SCHWARZ

Mr. Schwarz is Professor of Environment, Technology, and Society and Geography, Clark University, Worcester, Massachusetts. Trained as a civil engineer in Austria and the United States, Mr. Schwarz worked for the U.S. Army Corps of Engineers as an hydraulic designer, hydrologist, and planner. In his last assignment, he was project manager of the North Atlantic Regional Water Resources Study and the Northeast Water Supply Study. After retiring from the Corps, he joined the faculty of Clark. His research has included environment and development problems in the United States, Europe, and East Africa. He was a member of the academy Task Force on Climate Change in 1977 and of the recent AAAS committee on Climate Change and U.S. Water Resources. He has written a book on water planning, several book chapters, and numerous papers on water problems.

DANIEL P. SHEER, PH.D., P.E.

Dr. Sheer is President of Water Resources Management, Inc., a water resources consulting firm in Columbia, Maryland. Since founding WRMI in 1985, Dr. Sheer has worked for a variety of U.S. and international government agencies building simulation and optimization models to describe water resources systems for analysis, gaming, and computer-aided negotiating sessions. In 1980 Dr. Sheer became the first Director of the ICPRB Section on Cooperative Water Supply Operations on the Potomac (CO-OP). In this role, he was responsible for technical leadership and the coordination of a multi-agency program that produced and implemented joint operating policies and procedures in the Potomac River basin. Dr. Sheer received a B.A. in Natural Sciences and a Ph.D. in Environmental Engineering from Johns Hopkins University.

EUGENE Z. STAKHIV, PH.D.

As Chief, Policy and Special Studies Division, U.S. Army Corps of Engineers, Institute for Water Resources, Dr. Stakhiv oversees several programs that support the strategic planning, policy development, and research needs of the Corps. These programs include National Infrastructure Strategy, the National Drought Management Study, the Socioeconomic Impacts of Climate Change on Water Resources Management Research Program, and the Policy Studies Program (15 separate studies that encompass evaluating and developing policies for environmental evaluation, wetlands, international projects assistance, dredging, floodplain management, etc.). In addition, Dr. Stakhiv is co-chairman of the Hydrology and Water Resources Impact Assessment, a sub-group of Working Group II, U.N. Intergovernmental Panel on Climate Change (IPCC), and a member of Working Committee 4 (Plan Formulation and Evaluation) of the International Joint Commission's Great Lakes Fluctuating Levels Study. Dr. Stakhiv has a B.S. in Meteorology from the City College of New York, an M.S. in Physical Oceanography from the University of Rhode Island, and a Ph.D. in Water Resources Systems Engineering from Johns Hopkins University.

HEINZ G. STEFAN, PH.D.

Dr. Stefan is Professor and Associate Director of the University of Minnesota's St. Anthony Falls Hydraulic Laboratory. His current research activities are mostly in the areas of hydrodynamics and water quality dynamics. His research has related to physical and mathematical modeling of temperature regimes and heat budgets of lakes and rivers, dispersion of effluents, density currents, stratification and mixing in reservoirs and near water outlets, dissolved oxygen and productivity modeling, ice formation, and suspended sediment transport.

ROLAND C. STEINER, PH.D.

Dr. Steiner has worked with the Interstate Commission on the Potomac River Basin for 7 years on issues involving water quality, water resources management, and water supply in the Potomac River basin. He is both Associate Director for Water Resources and Director for Cooperative Water Supply Operations on the Potomac, with water resources allocation responsibilities for the Washington, D.C., metropolitan area. Dr. Steiner holds B.S. and M.S. degrees in Civil Engineering from the University of Pennsylvania and Stanford, respectively, and a Ph.D. from Johns Hopkins University. Prior to his present position, Dr. Steiner worked for 9 years in England and Wales for national and regional water and waste-water management agencies.

JAMES R. TUTTLE

Mr. Tuttle is currently Chief of the Water Control Division, Lower Mississippi Valley Division/Mississippi River Commission, U.S. Army Corps of Engineers, located in Vicksburg, Mississippi. He has 12 years of federal service. He holds a B.S. from the University of Mississippi and an M.S. from the Georgia Institute of Technology, both in Civil Engineering. He is a member of the Corps' Mississippi River Water Control Management Committee.

RICHARD WAHL, PH.D.

Dr. Wahl has been an economist in the Department of the Interior's Office of Program Analysis since 1979. In that capacity, he has spent most of his time analyzing water resources programs of the Bureau of Reclamation. He was a Visiting Fellow at Resources for the Future (RFF) during 1985 and a Visiting Fellow at the Natural Resources Law Center at the University of Colorado in 1988. He helped write the water resources section of Climate Change: The IPCC Response Strategies. His publications include "Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation" (1989): (with Brian Gray and Bruce Driver) "Transfers of Federally Reclamation Water: A Case Study of California's San Joaquin Valley" (1991); "Acquisition of Water to Maintain Instream Flows" (1990); "New Roles for the Bureau of Reclamation" (1989); and (with Robert K. Davis) "Satisfying Southern California's Thirst for Water: Efficient Alternatives" (1986). He received a Ph.D. in Applied Economics from Johns Hopkins University in 1978.

GEORGE H. WARD, JR., PH.D.

Dr. Ward specializes in the hydrodynamics and transport processes operating in natural fluid systems, including the atmosphere, ocean, and watercourses, in which he has performed research and project studies for 25 years. With an academic background in meteorology and fluid dynamics, his subject area has been rivers, lakes, and estuaries, and has ranged from special-purpose field experiments to model development and application. He is Associate Director of the Center for Research in Water Resources at the University of Texas at Austin.

DAVID M. WOLOCK, PH.D.

Dr. Wolock received a B.A. from Colgate University, an M.S. from Cornell University, and a Ph.D. from the University of Virginia. He has been an hydrologist with the U.S. Geological Survey since 1988 studying the effects of climate change on water resources.

VIII. Conference Agenda

The First National Conference on:

Climate Change and Water Resources Management

AGENDA

Monday, November 4, 1991

5:00–8:00	**Early Registration**	Pavilion Court
5:30–7:30	**Welcoming Reception**	Pavilion I–II

Tuesday, November 5, 1991

7:45–8:45	**Registration**	Pavilion Court
7:30–8:45	**Speakers Breakfast** *for the day's speakers*	Fiesta 1&2
9:00–Noon *chairperson*	**First Plenary Session** Mr. Kenneth Murdock *U.S. Army Corps of Engineers,* *Water Resources Support Center*	Pavilion I–III
9:00–9:10	**Introductory Remarks** Louis Saavedra, *Mayor of Albuquerque*	
9:10–10:00	**What Water Managers and Planners Need to Know About Climate Change and Water Resources Management** Dr. Peter P. Rogers, *Harvard University*	
10:00–10:50	**The Knowns and Unknowns of Climate Change — What Science Tells Us** Dr. William Kellogg, *National Center for Atmospheric Research*	
10:50–11:10	**Coffee Break**	Pavilion Court
11:10–Noon	**The Political and Institutional Constraints of Responding to Climate Change** David N. Kennedy, *California Department of Water Resources*	
Noon–1:30	**Lunch** Dr. Harlan Watson, *Speaker* *Deputy Assistant Secretary for Water and Science* *Science Advisor to the Secretary, U.S. Department of the Interior*	Pavilion IV–VI

2:00–5:30 **Regional Sensitivity to Climate Change** Albuquerque Convention Center
Simultaneous Sessions

a. WEST — Cimarron Room

chairperson • Dr. Stanley G. Coloff, *U.S. Department of the Interior*
rapporteur • Ms. Ann Ball, *U.S. Department of the Interior, Bureau of Reclamation*
• Dr. John Dracup, *University of California at Los Angeles*
• Mr. Charles DuMars, *University of New Mexico, School of Law*
• Ms. Linda Nash, *Pacific Institute*
• Dr. Dennis Lettenmaier, *University of Washington*
• Mr. Ronald (Rusty) J. Schuster, *U.S. Department of the Interior, Bureau of Reclamation*

b. SOUTHEAST — Dona Ana Room

chairperson • Mr. Joel Smith, *U.S. Environmental Protection Agency*
rapporteur • Dr. Cory Berish, *U.S. Environmental Protection Agency*
• Dr. William S. Cooter, *Research Triangle Institute*
• Dr. Barbara Miller, *Tennessee Valley Authority*
• Dr. John Schaake, *U.S. Department of Commerce, National Oceanic and Atmospheric Administration*
• Dr. Jurgen Schmandt, *University of Texas at Austin, School of Public Affairs*
• Dr. Daniel Sheer, *Water Resources Management, Inc.*

c. NORTHEAST — Aztec Room

chairperson • Dr. John E. Schefter, *U.S. Department of the Interior, Geological Survey*
rapporteur • Mr. Michael R. Krouse, *U.S. Army Corps of Engineers*
• Dr. Myron Fiering, *Harvard University*
• Dr. Paul Kirshen, *Massachusetts Water Resources Authority*
• Dr. David Major, *Social Science Research Council*
• Dr. David Wolock, *U.S. Department of the Interior, Geological Survey*

d. UPPER MIDWEST — Galisteo Room

chairperson • Mr. James Tuttle, *U.S. Army Corps of Engineers*
rapporteur • Dr. Gregory J. Wiche, *U.S. Department of the Interior, Geological Survey*
• Dr. Stewart Cohen, *Canadian Climate Center*
• Mr. Darryl Davis, *U.S. Army Corps of Engineers*
• Dr. Heinz G. Stefan, *University of Minnesota*
• Dr. Frank Quinn, *Great Lakes Environmental Research Laboratory*

Wednesday, November 6, 1991

7:30–8:45	**Speakers Breakfast** *for the day's speakers*	Enchantment A&B
9:00–Noon *chairperson*	**Second Plenary Session** Dr. Harry Lins, *U.S. Department of the Interior, Geological Survey*	Pavilion I–III
9:00–9:40	**What Climate Change Modeling May Tell in the Future** Dr. David Rind, *NASA/Goddard Institute for Space Studies*	
9:40–10:20	**Climate to Runoff** Dr. John Schaake, *U.S. Department of Commerce, National Oceanic and Atmospheric Administration*	
10:20–10:40	**Coffee Break**	
10:40–11:20	**Runoff to Management** Dr. Myron Fiering, *Harvard University*	
11:40–Noon	**Design Implications of Climate Change** Dr. Vit Klemes, *Consultant*	
Noon–1:30	**Lunch** Mr. Daniel C. Esty, *Speaker* *Deputy Assistant Administrator for Policy, Planning and Evaluation, U.S. Environmental Protection Agency*	Enchantment Room
2:00–5:30	**Adaptive Responses to Climate Change** Simultaneous Sessions	Albuquerque Convention Center

a. LONG RANGE PLANNING — Cimarron Room

chairperson
- Mr. James (Randy) R. Hanchey, *U.S. Army Corps of Engineers*

rapporteur
- Dr. Robert Brumbaugh, *U.S. Army Corps of Engineers*
- Dr. Benjamin Hobbs, *Case Western Reserve University*
- Dr. Eugene Z. Stakhiv, *U.S. Army Corps of Engineers*
- Mr. Roland Steiner, *Interstate Commission on the Potomac River Basin*

b. DEMAND MANAGEMENT — Dona Ana Room

chairperson • Mr. Kyle Schilling, *U.S. Army Corps of Engineers*

rapporteur • Dr. Peter Gleick, *Pacific Institute*

• Mr. Steven Estes-Smargiassi, *Massachusetts Water Resources Authority*

• Mr. Kenneth D. Frederick, *Resources for the Future*

• Dr. Richard Wahl, *U.S. Department of the Interior, Bureau of Reclamation*

c. SUPPLY DEVELOPMENT/MANAGEMENT — Aztec Room

chairperson • Mr. Rick Gold, *U.S. Department of the Interior,*
rapporteur *Bureau of Reclamation*

• Mr. Lew Moore, *U.S. Department of the Interior*

• Mr. J. Darrell Bakken, *Indianapolis Water Company*

• Dr. Kathleen Miller, *National Center for Atmospheric Research*

• Dr. Steven Rhodes, *National Center for Atmospheric Research*

• Dr. Kenneth Strzepek, *University of Colorado*

d. EXTREME EVENTS — Pecos Room

chairperson • Dr. Daniel Sheer, *Water Resources Management, Inc.*

rapporteur • Dr. Peter Comanor, *National Park Service, U.S. Department of the Interior*

• Mr. Gary Hester, *California Department of Water Resources*

• Dr. William Riebsame, *University of Colorado*

e. WATER QUALITY AND ECOLOGICAL SYSTEMS — Ruidoso Room

chairperson • Ms. Gwendolyn Williams, *U.S. Fish and Wildlife Service*

rapporteur • Dr. Joel Scheraga, *U.S. Environmental Protection Agency*

• Dr. Henry Jacoby, *Massachusetts Institute of Technology*

• Mr. William Painter, *U.S. Environmental Protection Agency*

• Mr. B. J. Miller, *Consultant*

Thursday, November 7, 1991

7:30–8:45	**Speakers Breakfast** *for the day's speakers*	Board Room East
9:00–Noon *chairperson*	**Closing Plenary Session** Prof. Harry Schwarz, *Clark University*	Pavilion VI
9:00–9:15	**Summary Regional Sensitivity Sessions** Mr. Joel B. Smith, *U.S. Environmental Protection Agency*	
9:15–9:30	**Summary, Adaptive Response Sessions** Dr. Eugene Z. Stakhiv, *U.S. Army Corp of Engineers*	
9:30–Noon *chairperson* *rapporteur*	**Panel Discussion, Issues for Water Management** • Prof. Harry Schwarz, *Clark University* • Mr. Thomas M. Ballentine, *U.S. Army Corps of Engineers* • Mr. J. Darrell Bakken, *Indianapolis Water Company* • Mr. James (Randy) R. Hanchey, *U.S. Army Corps of Engineers* • Dr. Gerald Hansler, *Delaware River Basin Commission* • Mr. Robert Varady, *University of Arizona* • Dr. Peter Gleick, *Pacific Institute* • Dr. Peter P. Rogers, *Harvard University* • Mr. Terry Lynott, *U.S. Department of the Interior, Bureau of Reclamation*	
Noon	**CONFERENCE ADJOURNS**	
1:00–4:00	**Closing Work Session for Conference Sponsors**	Board Room North

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13. ABSTRACT *(Maximum 200 words)*

Conference papers address issues of future water availability and future demand from the perspective of water resources managers. Papers address both practical and conceptual issues of hydrology and water management amidst a diversity of geographical region and response strategies.

Other papers address response to climate change as it may be influenced by developing scientific, political, economic, institutional, environmental and associated issues, conditions and determinants.

Papers which address assessments based on General Circulation Models, attempt to improve accuracy and the relevance of models to practical engineering solutions are also included.

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