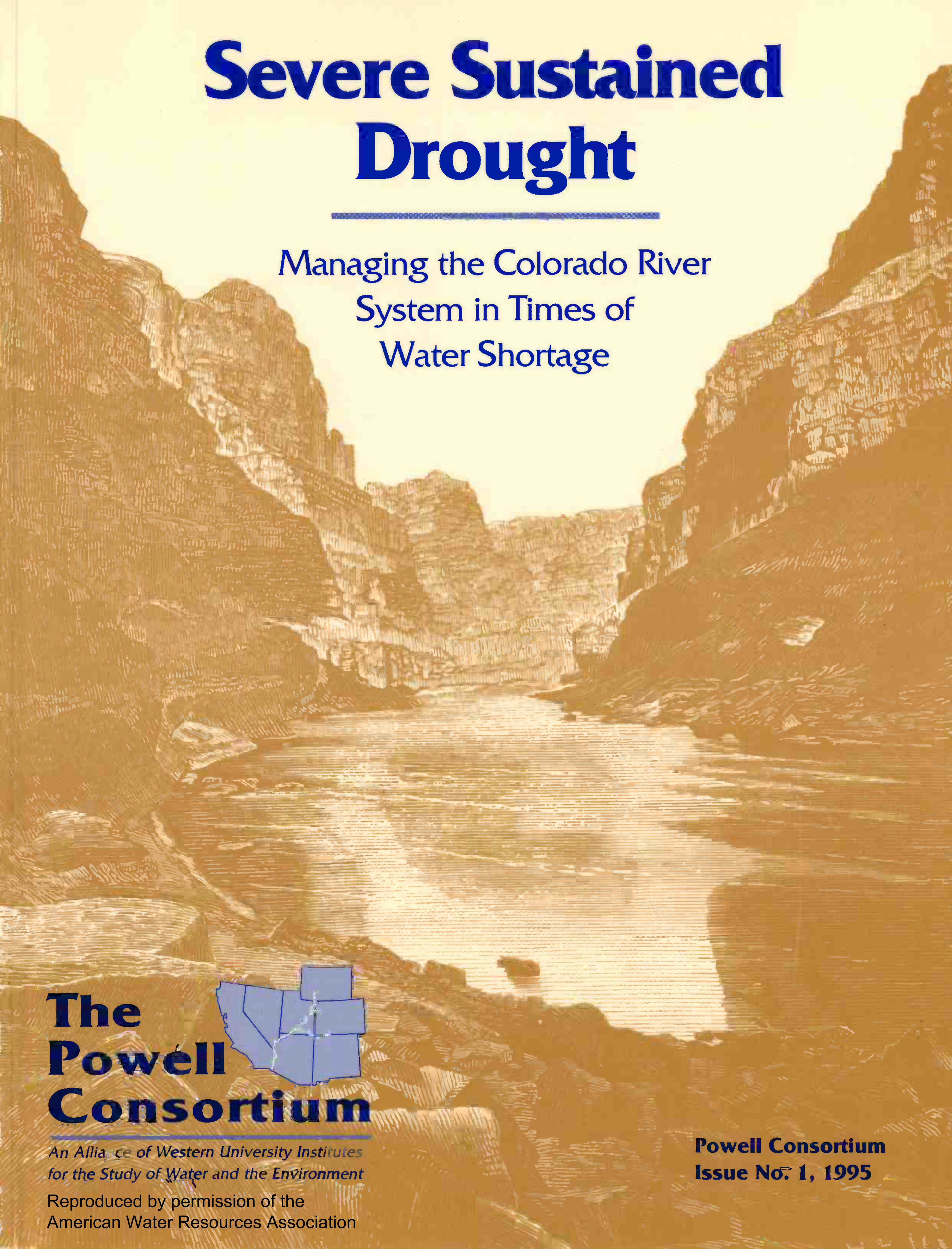

Severe Sustained Drought

Managing the Colorado River System in Times of Water Shortage

The Powell Consortium

An Alliance of Western University Institutes for the Study of Water and the Environment

Powell Consortium
Issue No. 1, 1995

SEVERE SUSTAINED DROUGHT
MANAGING THE COLORADO RIVER SYSTEM IN TIMES OF WATER SHORTAGE

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FOREWORD

The Colorado River in the southwestern United States is one of the most highly regulated and heavily utilized river systems in the world. It supplies water for domestic, agricultural, industrial, recreation, hydroelectric, ecological, and aesthetic purposes to seven states and two countries. It directly supplies part or all of the drinking water for over 30 million people and the interdependencies of its other uses have direct or indirect effects on additional tens of millions of people. Considerations about managing the Colorado River system range from maintaining bountiful agricultural production to maintaining endangered species found nowhere else. It is what the Powell Consortium has termed a mega-scale water supply and distribution system. Its management involves state, interstate, national, and international legal and institutional arrangements. This monograph sets forth results of a multi- and interdisciplinary research project begun in the early 1980s and completed in 1994. It has a complex and difficult funding history ranging from contributions of several hundred thousands of dollars by some federal programs down to a few hundred dollars from local funding sources. The study is about the nemesis of water supply systems in arid regions of the world – drought. The project has had a variety of titles – depending on timing and source of funds – but has become known collectively as the Severe Sustained Drought (SSD) study. It represents an effort to develop and understand the potential ramifications of drought in the Colorado River as we know it today. It stands as an example of much-needed attention to long-term planning for our water resources. Before you read individual papers – and we encourage you to read them all – a little perspective is perhaps in order.

Initial decisions about how to begin management and allocation of the Colorado River system were made early in this century and based upon a relatively short (approximately 20-year) record of flow in the river. The original agreement, signed in 1922 and ratified by the U.S. Congress, is called the Colorado River Compact. Subsequent modifications and refinements have occurred through additional compacts, treaties, and court decrees. Combined with operational criteria developed by the federal government and the states to implement these legal arrangements, the collective embodiment of this management system has come to be known as the "Law of the River." As our period of record for river flows has grown from a couple of decades to nearly a century, it has become widely accepted that the Colorado River typically has less water (10-15 percent less) than the compact allocation originally assumed. That means that when all water in the basin is used for its intended purpose, there will be a shortage. This eventuality has already produced immense concern and discussion at all levels of government and among users as to how supply and demand can be balanced.

The Severe Sustained Drought Study contemplates a much more dire water supply scenario than that which has occurred in the past century. Reconstruction of river flow records, based upon several centuries of data, suggests that periods of much reduced flow in the river have periodically occurred. These data are derived from analysis of growth rings in trees from around the Colorado River Basin states. Combining this information, the SSD researchers have created a highly plausible scenario of severe and sustained drought and used that as a means of assessing what the hydrologic, social, and economic impacts of such a drought would be under the current law of the river. As you will see, the impacts are substantial. The SSD researchers have also explored what possible combinations of changes in institutional arrangements regarding how the river is operated might be made to reduce or mitigate the impacts of such a drought. Institutional inflexibility suggested in the SSD study provides a significant challenge to resource planners and water managers in crafting solutions. Such solutions must somehow be equitable across the spectrum of society which depends in a variety of complex ways on the Colorado River.

The Powell Consortium expresses its appreciation to the authors of this volume for their expertise and diligence in completing the research and its publication. We are pleased to have been a sponsor of this research effort and to offer this monograph on Severe Sustained Drought in the Colorado River Basin for your consideration. The Consortium also gratefully acknowledges the cooperation and support of the American Water Resources Association in granting permission to reproduce the papers originally published in the *Water Resources Bulletin*. We thank all other sponsors and contributors to the research effort.

Steven P. Gloss, President
Powell Consortium

Honest investigation is but the application of common sense to the solution of the unknown."

John Wesley Powell
October 1884

THE POWELL CONSORTIUM is an alliance of seven Water Resources Research Institutes and Centers from the states of Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming formed to work on water resources problems of the Colorado River/Great Basin region. The Consortium is named in recognition of John Wesley Powell (1834-1902), geologist, teacher and philosopher, whose pioneering explorations of the Colorado River Basin became legendary.

POWELL CONSORTIUM OBJECTIVES

To organize and conduct scientific studies and outreach programs on water and other natural resource issues important to the region.

To conduct interdisciplinary research and development for government agencies, public and private foundations and other entities both corporate and individual.

To provide a visible and accessible interface among water scholars from universities and western water resources managers, planners and governmental officials.

To disseminate and exchange scientific knowledge and information through technical reports, journal publications, symposia, workshops, short courses, and scientific meetings.

BACKGROUND

Beginning in the early 1970's, seven Water Resources Research Institutes and Centers from the states of Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming formed an informal consortium to work on water resources problems of the Colorado River/Great Basin region. This group adopted the name the Powell Consortium on June 2, 1991, and subsequently entered into a seven state agreement to more formally articulate common goals and operating procedures.

The Consortium is named in recognition of John Wesley Powell (1834-1902), geologist, teacher and philosopher, whose pioneering explorations of the Colorado River Basin became legendary. Like Powell, scientists from the Colorado River Basin continue to marvel at the complexity and importance of water resources and see a pressing need to promote and facilitate research and education on water resources and other important environmental issues to the region.

The Consortium utilizes the collective expertise of its member universities and over 20 other cooperating universities to develop and disseminate knowledge to solve problems of the Colorado River/Great Basin region and other arid regions of the world. As inspired by Powell, the Consortium seeks to improve the technical and scientific basis for decision making on water and environmental issues through honest investigation and the application of common sense to problem solving.

CONSORTIUM ORGANIZATION

Policy and general guidance is provided by the Board of Directors who consist of the water research institute/center directors from the seven member states. The Consortium serves as the coordinating entity to integrate project information, provide overall program guidance and serve as the principal communication interface between project participants, project sponsors and user groups.

The Consortium identifies research and outreach priorities, potential funding sources for projects which fit the priorities and develops proposals to secure funding. Funding for the Consortium projects is between a sponsor and a "Lead Institute" selected by the Board to administer the project on behalf of the Consortium as a "Powell Consortium Project."

The Board receives advice from User Committees. These groups include federal and state agency executives, irrigation and metropolitan water districts, environmental organizations and other interested groups. Input from these committees assures that research and outreach activities of the Consortium focus on the most relevant problems.

FOCUS OF RESEARCH AND EDUCATION

While the scope of work conducted by the seven member institutes is very broad, the Consortium's present focus of collaborative research and education is in the following areas:

Water Resources Management – Studies on the institutional management of mega-scale water supply and distribution systems.

Analysis of Water Law and Policy as they affect the implementation of creative solutions to water planning and management in the region.

Ground Water – Studies and technology transfer related to the quality of ground water, its movement, management, protection, and remediation.

Educational Training and Outreach – Development of new programs for graduate level training of environmental regulators and agency personnel.

Water for Environment Values – Studies related to ecologically-based water relationships associated with wetlands, riparian areas, instream flows and endangered species.

Climate, Drought and Global Change – Impacts on water resources, hydrology, and related environmental issues.

INSTITUTIONAL CAPABILITIES OF THE POWELL CONSORTIUM

Members of the Powell Consortium have collaborated on a variety of research and outreach programs for nearly 20 years. The consortium not only draws on the considerable expertise and resources of their host universities, but also other universities in the Powell Consortium states. Under the federal Water Resources Research Act of 1964 which established the institute program, the institutes were mandated to serve all institutions of higher education within the state, enabling strong cooperative relationships. The institutes all maintain active advisory boards and have extensive cooperative ventures and strong ties with other water, natural resources and environmental management agencies and private organizations.

The Institutes and Centers of the Powell Consortium are all located at the Land Grant Institutions in their respective states. These Institutions are all fully accredited and are recognized as the major research universities in the region. All have established national and international reputations in various aspects of water resources research.

Members of the Powell Consortium collectively generate approximately $17.5 million per year in total funding from federal and non-federal sources. Non-federal sources (state, private, etc.) make up about 60% of the total. There are over 250 currently active research projects among members of the Powell Consortium which involve training of over 360 graduate and undergraduate students.

Each institute of the Powell Consortium publishes one or more newsletters reaching an audience of close to 60,000 readers. In addition, member institutes sponsor or cosponsor nearly 20 water conferences per year.

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COPING WITH A SEVERE SUSTAINED DROUGHT ON THE COLORADO RIVER: INTRODUCTION AND OVERVIEW[1]

Robert A. Young[2]

ABSTRACT: In arid regions of rapid economic and population growth, adverse effects of droughts are likely to be increasingly serious. This article presents an introduction and overview of the papers collected in this special issue of the *Water Resources Bulletin*. The papers report on the second phase of a study of the impacts of and responses to a potential severe sustained drought in the Colorado River Basin in the southwestern U.S. The analyses were performed by a consortium of researchers from universities and the private sector located throughout the Basin. Tree ring studies suggest that droughts of duration and magnitude much more serious than any found in the modern records probably occurred in the Basin during earlier centuries. Taking the present-day configuration of the storage and diversion structures and the economic conditions in the Basin as the base-point, the general objectives of the study are three: first, to define a representative Severe Sustained Drought (SSD) and assess its hydrologic impacts; second, to forecast the economic, social and environmental impacts on the southwestern U.S.; and finally, to assess alternative institutional arrangements for coping with an SSD. The evaluation of impacts and policies was conducted with two distinct modeling approaches. One involved hydrologic-economic optimization modeling where water allocation institutions are decision variables. The second was a simulation-gaming approach which allowed "players" representing each basin state to interact in a real-time decision making mode in response to the unfolding drought.
(KEY TERMS: water policy; drought; Colorado River; systems analysis; water law; modeling; water institutions.)

INTRODUCTION

The potential for the occurrence of drought and the associated adverse consequences for the economy, polity, and society is an ever present concern in arid regions such as the southwestern United States. In regions of rapid economic and population growth, adverse effects of droughts are likely to become increasingly serious. In the already arid southwest, drought does not necessarily introduce new problems; but it is likely to exacerbate resource conflicts which are already present and will become ever more serious as growth in water demands continues. Conflicts among consumptive and nonconsumptive water uses; between environmental and economic objectives; among states, regions, and nations are already with us. Severe drought would force an earlier attention to dealing with these issues. Droughts are certain to recur, so arid regions are well advised to be prepared with policies which will respond to this inevitability (Wilhite, 1993).

The papers collected in this special issue document the second phase of an effort to anticipate the likely hydrologic, environmental, economic, and social impacts of a severe, multiyear drought in the southwestern United States and to assess alternative policy responses to such a drought. The suggestion for an interdisciplinary research program to study the impacts of a severe sustained drought in the southwestern U.S. arose at a conference sponsored by the Arid and Semi-Arid Lands Directorate of the Man and the Biosphere Program, U.S. Department of State, held at Monterey, California, in 1982 (Englebert and Scheuring, 1984). One of the Conference panelists, Dr. Harold Fritts of the Laboratory for Tree Ring Research, University of Arizona, presented tree ring evidence from the southwestern U.S. implying that much more extreme and extended droughts were experienced in the past several centuries than have been observed in the modern records (Fritts, 1984). Professor Gilbert F. White of the University of Colorado amplified upon this theme in his summary and overview remarks at the close of the conference, and among other points urged the importance to the southwest of anticipating and preparing for severe

[1]Paper No. 95105 of the *Water Resources Bulletin*. **Discussions are open until June 1, 1996.**
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and sustained droughts (White, 1984). The prospect of prolonged severe drought in the southwest began to be addressed a few years later at a conference focused on the future management of the Colorado River (e.g., Kneese and Bonem, 1986; Clyde, 1986).

Subsequently, the Arid and Semiarid Lands Directorate initiated planning for a major study of the nature, potential impacts, and policy responses to a severe sustained drought in the southwest. An interdisciplinary team of researchers from universities in the Colorado River Basin states developed a two-phase approach, and the Man and the Biosphere Program supported the first phase work. The Phase I report (Gregg and Getches, 1991) provided initial analyses of tree ring evidence for severe sustained droughts in the southwest, and it included studies of the hydrologic and water quality implications, as well as initiating legal, political, and economic analyses of the ramifications of coping with such droughts.

STUDY SETTING

The Colorado River, whose major sources are in the Rocky Mountains, is the major river system in the southwestern United States. Its watershed includes portions of the states of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming (as well as a part of Mexico). In this generally water-short environment, it provides valuable water for agriculture, households, commerce, and industry, as well as contributing important hydroelectric power and recreational, fish and wildlife, and environmental benefits. A substantial amount of native flow is exported from the basin, primarily to southern California, but also to the Colorado Front Range metropolitan area, to central Utah, and to New Mexico. By treaty, Mexico receives 1.5 million acre feet, about one-tenth of the estimated average virgin flow. The Colorado is now fully utilized for offstream purposes; its waters reach the Gulf of California only during occasional high flow periods. Anticipated continued growth in population and income throughout the Basin will put increasing stress on the limited water resource.

Systematic river flow measurements in the Colorado River Basin, which began only a little over a century ago, show considerable fluctuation in annual water supplies and include some time intervals of persistent low flows. However, tree ring studies extend our understanding of the climate back several centuries prior to the availability of stream flow records. These analyses suggest that periods of low precipitation of more extreme duration and magnitude than can be found in the modern record probably occurred in the Basin. The most serious of these periods was a several-decade period in the late 1500s. During the present century, the southwestern states have come to rely on near normal Colorado River flows, but as demand for the River's flows continue to increase when a period of severe inadequacy returns to the region, significant economic, social, and environmental impacts can be foreseen.

The Colorado River Basin has been the site of unusual efforts to prevent drought impacts to water users, particularly to those in the Lower Basin. The U.S. Bureau of Reclamation has constructed water storage facilities with a capacity of roughly four times the annual flows. This massive storage capacity renders the issues of drought impact unimportant during normal climatic fluctuations. However, under extreme climatic conditions, drought management could become significant.

OVERVIEW: SCOPE AND OBJECTIVES

The present analysis extends the earlier Phase 1 studies with a series of detailed impact assessments and modeling studies, complemented by formal policy evaluations. It was conducted by an inter-disciplinary team from the Universities of Arizona, California, Colorado, Nevada, and Wyoming, plus faculty at Colorado State and Utah State Universities and the consulting firm Hydrosphere, Inc., based in Boulder, Colorado. Included on the team were engineer/hydrologists, tree ring scientists, attorneys, environmental scientists, economists, sociologists, and public administration specialists. The study group was overseen by a consortium of the Water Research Institutes in the Colorado River Basin states, with major funding provided by the U.S. Interior Department and the U.S. Army Corps of Engineers.

Research Objectives

Taking the present-day configuration of the storage and diversion structures and the economic conditions in the Basin as the base-point, the general objectives of the present Phase II study were three: first, to assess the hydrologic impacts of a Severe Sustained Drought (SSD); second, to forecast the economic, social, and environmental impacts on the southwestern U.S.; and finally, to assess potential alternative institutional arrangements for coping with an SSD. The papers collected here are largely condensations and revisions of the chapters appearing in the Phase II project completion report (Young, 1994).

Conceptual Framework

First, we take as axiomatic that managing water resources and associated natural environments requires an interdisciplinary strategy, drawing on the best in both natural science and social science disciplines. Much of the interdisciplinary approach used in this study can trace its roots to the pioneering work by the Harvard Water Program (Maass *et al.*, 1962), which drew upon the emerging capabilities to use computers to model combined hydrologic and economic systems and to assess water development and management policies.

Secondly, our overarching methodology owes a clear debt to the concept of multiobjective water resource planning, such as that set forth in the U.S. Water Resources Council's *Principles and Standards for Water and Related Land Resource Planning* (1973), and the Council's *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies* (1983). Those documents set forth an evaluation system which required systematic consideration of economic, environmental, and social factors following from proposed human interventions into water resource systems. The economic considerations were embodied in the National Economic Development (NED) account, which directed how beneficial and adverse economic effects were to be measured. [These techniques are also called benefit-cost analysis. Schmid (1989) provides a recent comprehensive text on benefit-cost analysis, while Pearce and Turner (1990) cover the topic with a focus on natural resource and environmental issues.] *Principles and Standards* included a "Social Well-Being" account to capture social impacts. The Environmental account eventually came to rely on NEPA-type environmental impact studies to take into account potential environmental aspects. In application to the severe sustained drought (SSD) issue, the distinct evaluative formats of the various social, economic, legal, and policy disciplines are drawn upon in the present study.

A third source of conceptual apparatus is the body of writings on formulating and evaluating alternative policies for human adjustment to natural hazards. This literature owes much to the writings of Gilbert White and his associates (for example, Burton *et al.*, 1993). Their natural hazards paradigm stresses the linkages between the uncertain events flowing from the processes of natural systems and human use of the environment. The interaction of extreme events with human activities produces hazards and also influences responses to them. White identified three types of human adjustment or response (aside from simply accepting the loss) to the risks of natural hazards. One response is to modify the burdens of loss by spreading the impact more widely, such as with public disaster relief programs or with disaster insurance. For droughts, insurance programs for farmers against crop yield losses are an example of the first type of response. The second type of adjustment is to modify the hazard event. In the case of drought hazards, construction of water storage and conveyance structures is the standard modification to reduce drought impacts. The policy of dam construction to reduce vulnerability to droughts perhaps has reached its apogee with the large dams in the Colorado River Basin, which can store four years average native flow of the river. The third type of response is to modify human vulnerability to hazard. This group of responses focuses on modifying the behavior of the humans at risk to the hazard. For the case of droughts, examples of policies to modify vulnerability include changes in operating rules and laws governing the management of water. (In the case of drought, the second and third types are closely interrelated, because modifying vulnerability often means changing the operating rules for dams and reservoirs.) We assume no changes in water storage and diversion structures in the Colorado Basin, so it is the class of vulnerability modification that receives the most attention in this study of potential responses to drought.

The research team believes that this effort is unique in a number of ways. Most drought assessments have been retrospective, seeking to assess the negative impacts after the fact and to describe human responses and adjustments to drought (Warrick, 1975; Easterling and Riebsame, 1987). Such studies provide valuable understandings of the consequences of drought and help planning for mitigation of future drought periods. The present study attempts to employ modeling to anticipate impacts of droughts and to assess alternative policy responses. While anticipatory treatments of drought impacts are not unique, the scope in time and space, the interdisciplinary, interuniversity and interagency collaboration, and the research tools applied are, we believe, unprecedented in drought research.

Definition of Drought

The initial step was to select a representative SSD for study. Drought is defined differently by different disciplines, and the choice of a study drought required careful consideration. Numerous definitions of drought have been proposed (Wilhite and Glantz, 1987). One approach defines drought in meteorological terms – e.g., as limited or no rainfall within some specified time period. However, such a method cannot distinguish between drought and general aridity.

Agriculturally or ecologically-oriented approaches focus on shortages of soil moisture relative to plant evapotranspiration needs, while the hydrologic approach might employ streamflow or ground water levels relative to long-term averages.

Most definitions, as well as common usage, share the point that drought is a situation of scarcity relative to "normal" conditions of precipitation, evapotranspiration, or river flow. Drought refers to an occasional situation, not permanent scarcity. Further, a definition of drought must be based partly on demand-side, human considerations, not solely on meteorological or hydrologic factors. However, no general agreement exists to guide the selection of a definition.

For this study, we chose a hydrologic measure as our basic indicator of drought: river flows relative to long-term averages. However, the hydrologic measure was derived from tree ring studies of long-term climatic behavior. We commenced the hydrologic analysis with an estimated measure of native flows at a selected point in the basin. The specific measure is annual flows at Lees Ferry – just below Glen Canyon Dam in northeastern Arizona – the point where convention and law divides the Colorado into Upper and Lower Basins. (Selection of a hydrologic measure intentionally confines the analysis to impacts and policy adjustments explicitly linked to river flows. Limits on research resources precluded any consideration in this study of the effects of low precipitation on ecology, society, and economy – other than those associated with river flows.)

Because drought is by definition a rare event, the number of occurrences in the observed streamflow record is small, so the risk assessments are uncertain. Tree ring reconstructions of streamflow offer a physical basis for the extension of hydrologic records further back than observed records and thus provide a window into the past that yields additional information on the magnitude and frequency of droughts. Tree ring streamflow reconstructions, however, are far from perfect, and their limitations must be recognized.

The representative 38-year drought period adopted for this study is patterned after (but not identical to) the most severe and long-lasting dry period identified by the tree ring studies. The drought chosen for evaluation includes a period of unusually low flows lasting about two decades, followed by a period of high flows long enough for mean annual inflow to return to its long-term average.

GENERAL APPROACH

Humankind has altered the Colorado River's native flow regime with both structural and institutional means. The federal government has provided a highly developed water storage and distribution system in the southwestern United States to provide security against droughts. Lakes Mead and Powell, the largest elements of that system, each can store more than two years' average native flow of the Colorado. To complement the extensive set of storage and diversion facilities, the basin states, joined by the federal government, have developed a set of institutional arrangements for operating the River, termed the "Law of the River." These rules are a combination of interstate compacts, federal statutes, Supreme Court decisions, the Mexico treaty, and a set of detailed operating procedures adopted by the Department of the Interior. The Law of the River assigns consumptive use limits and priorities to the various states to meet a variety of contingencies. As demands for water in the basin have grown, however, this large interlinked storage and institutional system may now be susceptible to sustained regional shortages of water supply.

The first component of the study was, for each year of the representative drought, to predict overall native flows and then to break these down into water availabilities at key locations in the Basin. Concurrently, socio-economic conditions in the region for future decades were projected. The analysis assumes a drought would begin at the time of the study's commencement – i.e., 1990. These hydrologic and socioeconomic projections provide the basis for the impact assessment and the institutional analyses that are the primary objectives of the study.

The study's second component was a legal and institutional assessment, designed to identify and investigate alternative legal and organizational arrangements which could be used to increase capacity for preparing for and coping with SSD.

A third, concurrent component was to estimate damages or impacts from droughts on economic sectors (including both instream and offstream beneficiaries), on social considerations, and on the environment.

These three components were then incorporated into two complementary types of interdisciplinary modeling assessment studies. One study is a computer optimization which evaluates economic impacts on instream and offstream water users of alternative policy instruments.

The second study consists of a dynamic "gaming" phase, in which an interactive computer program designed to represent impacts of policies chosen in real time by players representing various basin interests is developed. The purpose of this portion of the study was to identify changes in operating rules which might enable the region to reduce potential drought damages. Researchers, acting in the role of "water managers" who represent various state and federal interests, responded to an unfolding drought scenario and interacted with each other collectively, applying and changing management rules under which the River is managed.

SUMMARIES OF THE INDIVIDUAL ARTICLES

The articles in this special issue can be grouped into three sections and a summary of findings and recommendations. The first section develops the hydrologic implications, beginning with tree ring evidence, continuing with the virgin hydrology implied by the tree ring evidence, and concluding with the hydrology of the River, with its present complement of dams, reservoirs, and diversion structures.

Hydrologic Studies

"The Tree-Ring Record of Severe Sustained Drought in the Southwest," by dendrochronologists David Meko, Charles W. Stockton and W. R. Boggess, reviews the tree ring record of severe droughts in the southwestern U.S. They first discuss the physical concepts of dendrohydrology relevant to the delineation of severe sustained drought and then turn to an evaluation of tree ring evidence on severe droughts in the interior Southwest. Meko *et al.* (1995) first cover studies based on relatively short but well-replicated data, defined as the period since 1580. Next they turn to earlier evidence, which is much more spotty. They show evidence that several past droughts were both more severe and longer than any documented in historical records. Cautioning that streamflow reconstructions from tree rings are uncertain, they conclude that the most severe sustained drought on the Colorado River is estimated to have occurred in the period 1579-1598.

David G. Tarboton's contribution, "Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States" develops hydrologic scenarios of regional water shortage to be used in the broader study of the economic, political, social, and environmental impacts of severe sustained drought in the southwestern U.S. The paper develops severe sustained drought scenarios for the Colorado River based on recorded streamflow as well as streamflow reconstructions from tree ring measurements. They do not necessarily include some severe short droughts. Since the drought scenarios were defined in terms of Lees Ferry tree ring reconstructed streamflow, to use them with the simulation models developed for the subsequent policy analyses required disaggregation in time (into monthly time steps) and in space (to the source inflow at each of 29 source flow locations). This was done using a statistical disaggregation package.

Drought scenarios in the Basin studied by Tarboton are defined in terms of aggregate annual flows (in million acre feet-maf) at Lees Ferry. The scenarios include:

1. Colorado River Basin Severe Drought. The period 1579 to 1600 is the most severe sustained drought that occurred in the tree ring reconstruction of Lees Ferry streamflow (Meko *et al.,* 1995) dating back to 1520. It is characterized by a 22-year mean streamflow of 11.1 maf with mean streamflow over the first 17 years (1579 to 1595) of only 10.5 maf. The mean of recorded native streamflow at Lees Ferry is 15.2 maf. This drought is estimated to have a return period between 400 to 700 years.
2. Colorado Drought in Historic Record. The period 1943 to 1964 is the most severe drought that occurred in the observed Lees Ferry streamflow record dating to 1906. It is characterized by a 22-year mean flow of 13.4 maf (compared to the observed mean of 15.2 maf). The return period is estimated to be between 50 and 100 years. This drought is defensible as likely to recur regardless of uncertainty in the tree ring reconstructions of streamflow.
3. Colorado Rearranged Severe Drought. This is an artificial scenario formed by taking the flows in scenario 1 above and assuming they occur in decreasing order so that the lowest flows come at the end. It is characterized by a 16-year mean flow of 9.6 maf (compared to the observed mean of 15.2 maf) and has a return period from 2000 to 10,000 years or more. This is an extreme, perhaps even unrealistic scenario, designed to discover how the system would respond to a truly catastrophic drought.

The Colorado rearranged severe drought was the "representative drought" that served as the basis for most of the subsequent analyses documented in this issue.

In the next paper, "Impacts of a Severe Sustained Drought on Colorado River Water Resources," by Benjamin L. Harding, Taiye B. Sangoyomi, and Elizabeth A. Payton investigate the hydrologic impacts of the most severe drought reconstructed by Tarboton (1995), taking account of the existing human-made structures and institutional arrangements. The analysis is designed to translate the effects of reduced native flows in the representative drought into streamflows, reservoir storage, depletions, hydropower production, and salinity at points along the river, given the existing structures for storage and diversion, and given whatever institutional set of rules are being examined in the policy analyses. Harding *et al.'s* (1995) analysis was carried out using the Colorado River Network Model, hereafter referred to by the acronym CRM. This model is a network flow model which uses an out-of-kilter algorithm to perform at each time-step a static optimization that represents water allocation for a given set of priorities in a river basin network. CRM represents the basin in a manner similar to the U.S. Bureau of Reclamation's Colorado River Simulation Model, but at a somewhat more aggregate level of detail. It uses a monthly time-step and represents 107 river reaches, 14 major reservoirs, 29 inflow points, and 265 individual consumptive use points. CRM also provides estimates of hydropower production (as a function of flows and generating head) as well as salinity concentrations.

Legal, Administrative and Social Aspects

Following these hydrologic studies, the second section of the issue consists of two articles which address legal, administrative, and political aspects of the problem and one reporting on the social impact studies.

"The Law of the Colorado River: Coping With Severe Sustained Drought" – from the perspective of its effect on water allocation decisions – is the subject of the analysis by legal scholars Lawrence J. MacDonnell, David H. Getches, and William C. Hugenberg, Jr. They present an interpretation of how water would be allocated according to existing legal priority during a severe sustained drought episode. Although the "Law of the River" is not technically a priority system, either express or implied priorities are created among those legally entitled to use water by the compacts, court decisions, statutes, and operating regulations that comprise the Law. Because these priorities would presumably govern allocations in a severe drought situation, the analysis seeks to make the priorities more explicit, to identify areas of uncertainty, and to assess the flexibility of the existing allocative institutions in meeting a severe drought. MacDonnell and colleagues conclude by examining potential flexible responses within the existing framework. Additional steps beyond the present Law of the River framework, such as water banking and water marketing are also discussed.

In the next article, "Institutional Options for the Colorado River," Douglas S. Kenney examines institutional options from the perspective of political science and public administration. He begins by assessing the political environment of the Colorado River management institutions, with emphasis on the mechanisms for conflict resolution. He then lays out a set of institutional requisites for effectively coping with natural hazards, including droughts. He also compares Colorado River institutional arrangements with those found in other major river basins. Next, he identifies seven types of institutional options for interstate water resource management: interstate organizations such as compact commissions and interstate councils; federal-interstate organizations such as basin interagency committees, interagency-interstate commissions, and federal-interstate compact commissions; and federal organizations such as federal regional agencies (e.g., the Tennessee Valley Authority) and the single federal administrator (the type now operating the Colorado River). Kenney concludes with prescriptions which offer the potential for improving the ability of the region to respond to a wide range of resource issues under a number of economic growth and hydrologic scenarios. He proposes nonsubstantive solutions to specific issues, but institutional arrangements which create forums and processes by which complex and divisive issues can be resolved.

In "Social Implications of Severe Sustained Drought: Case Studies in California and Colorado," Richard S. Krannich, Sean P. Keenan, Michael S. Walker, and Donald L. Hardesty developed social impact indicators of drought. Although water management systems and water users can likely adapt to short-term periods of water scarcity, response capabilities are likely to be severely strained when drought conditions are severe and persistent. Human social systems, particularly in the southwest, are closely linked to ecology and environment, and major disruptions have been documented when environmental disruptions confront communities with extreme conditions. Because severe hydrologic drought conditions have received little recent study by sociologists, Krannich and his associates chose to conduct original surveys of public attitudes and potential responses to water shortages and management alternatives. Their two study areas were in the Grand Valley of western Colorado and the San Joaquin Valley area of central California. Water is of central importance in the economy and social well-being of both these areas. The Grand Valley study area, in which is located the small city of Grand Junction, Colorado, is in an arid climate and depends on the Colorado River for agricultural, municipal, and industrial water supplies. Water issues are a matter of considerable interest, although the region's favorable location on a major river has helped it avoid experiencing serious threats of water shortage. The San Joaquin study area encompasses the Bakersfield metropolitan area and much of surrounding Kern County. This area is not directly linked to the Colorado River but depends on a highly complex water supply and delivery system that relies on surface water delivered from northern California and on extensive ground water pumping. Data were collected by self-administered surveys in each area. Respondents were questioned on the usual sociodemographic variables and on a number of specific questions pertaining to the potential impacts of drought, vulnerability to drought, and attitudes regarding public policy responses to drought. Specifically, questions were asked to elicit perceptions of the likelihood of a severe sustained drought and how such an event would financially affect them. Also, the acceptability of strategies for responding to drought were studied in both areas.

Modeling and Policy Analysis Studies

The third section of the issue contains two impact analysis studies, which present environmental and economic impact assessments of the effects of a severe sustained drought, and three modeling studies, which integrate instream and offstream considerations and tests of alternative policies. These efforts employ optimization, gaming and simulation techniques. As set up, the first two papers document the environmental and economic assumptions underlying the subsequent three modeling studies. The modeling studies employ optimization, gaming, and simulation techniques.

In "Assessing Environmental Effects of Severe Sustained Drought," the first impact analysis study, Thomas B. Hardy describes his derivation of the environmental impact measures employed by the basin models of impacts used in the subsequent gaming exercises. Hardy developed evaluation criteria for reservoir and stream resources to aid in assessing effects of water allocation decisions during an SSD. Seven categories of flow-dependent environmental resources were identified so that resource states associated with reservoirs or river reaches can be highlighted in the subsequent gaming analysis. The hydrologic models directly simulate impacts of water management decisions on four of the categories: threatened, endangered, or sensitive fish species; wetland and riparian habitats; national and state wildlife refuges; and fish hatcheries and other flow-dependent facilities. Two additional categories – cold and warm water sport fisheries – were not modeled explicitly as environmental variables but were included elsewhere in the economic evaluation of Colorado River-based recreation. For each of the four resource categories noted above and for each time step in the analysis, an assignment was made to one of four possible environmental states: stable; threatened; endangered; or extirpated. Reservoir levels or stream flows determine the environmental state at each time step for selected river reaches. Research resource limitations preclud-ed any site-specific data collection. The Tennant Method represents the most defensible, accurate, and reliable approach relying on aggregated water flow data. It is based on numerous observations and professional judgments concerning the adequacy of various discharge rates in meeting the needs of aquatic resources. Hardy concludes by illustrating how linking the hydrologic and environmental measures can show the effects of water management decisions on environmental resources in the event of impaired flows or storage.

In "Competing Water Uses in the Southwestern United States: Valuing Drought Damages," the second impact analysis study, economists James F. Booker and Bonnie G. Colby summarize the measures developed to assess economic losses from drought. Demand or marginal benefit functions (which measure economic value as a function of water supply) for Colorado River water use were developed for both instream and offstream uses according to standard techniques for economic valuation of nonmarketed goods and services. Marginal economic benefits decline as water supply increases (other factors held constant), or conversely, they increase as drought removes water from a region. Irrigation benefit functions were developed from linear programming (LP) models of water allocation options under site-specific soil, climatic and market conditions. The LP models are formulated so as to yield a net benefit (profit) for each point on a hypothesized range of water availabilities. Irrigation benefit functions were developed for representative areas in the Upper and Lower Basins. Lower Basin demand estimates were formulated to incorporate water quality (salinity) considerations as well as water supply. Salinity damage estimates were developed from U.S. Bureau of Reclamation reports, corrected for certain conceptual and measurement overestimation errors believed to be in the federal analyses. Residential water demand functions were developed by reference to previous demand studies.

Instream economic benefits include hydropower, salinity abatement and recreation. Hydropower production depends on the quantity of water flowing through turbines, the distance the water falls ("head"), and the efficiency of the generating plant. Both the quantities and the head are adversely affected by drought and are provided for the various scenarios in the hydrologic element of the basin models. The value per kilowatt hour of hydropower produced was estimated by the costs avoided by utilities in substituting hydropower for generation at existing thermal plants. Recreational uses of Colorado River waters provide increasingly important, although nonmarketed benefits. Monetary demand functions for recreational use of water were approximated for flatwater recreation on major reservoirs and for whitewater recreation in the Grand Canyon from previous studies in the Basin and elsewhere. Rafting and fishing benefits elsewhere in the Basin had to be ignored due to lack of data, so total recreational impacts of low flows are underestimated.

In "Hydrologic and Economic Impacts of Drought Under Alternative Policy Responses," the first modeling study, James F. Booker describes the formulation and operation of the Colorado River Institutional Model (CRIM), an optimization model integrating hydrologic, economic, and legal-institutional elements pertinent to managing Colorado River waters. CRIM is designed to estimate the economic impacts of alternative water allocations and to study the impacts of alternative policy and institutional responses to a severe sustained drought. This version of CRIM is solved on an annual basis throughout the reference drought period, with reservoir storage updated annually. For estimating economic losses due to drought, CRIM uses the benefit functions reported by Booker and Colby (1995). (In order to incorporate economic, institutional, and policy considerations, CRIM sacrifices some hydrologic and time-step detail as compared with Harding *et al.'s* (1995) CRM model described earlier in this issue). Solutions provide estimates of water quantity and quality (salinity) at each of 22 river nodes, as well as active and dead storage, evaporation, hydropower production and value and flatwater recreation benefits at each of seven major reservoirs. Economic benefits of alternative water allocations are provided for each of 32 offstream consumptive use locations. Formulated as a nonlinear optimization problem, CRIM simultaneously solves the economic impact and water allocation problems, subject to assumed policy scenarios. Economic impacts of an SSD were estimated by operating CRIM for several policy scenarios. The basic scenario was the existing "Law of the River" (Getches *et al.,* 1995). Other proposed policy responses included three basic types: first, changes in river management procedures; second, changes in legal environments; and third, market-based alternatives.

In "A Gaming Evaluation of Colorado River Drought Management Institutional Options," the second modeling study, James L. Henderson and William B. Lord adopt the technique of real-time simulation and gaming experiments to analyze changes in operating rules for allocating and managing Colorado River water which could help reduce adverse impacts of a severe sustained drought. "Gaming" refers, in this context, to the technique of placing subjects in a situation which requires them to make collective decisions among hypothetical policy options, the consequences of their choices being shown to them as the game proceeds. Playing this type of hypothetical game can begin the evaluation of alternative policies at far less cost than trying out the options in a real environment. Gaming can be thought of as a simulation of the collective choice process so that improved operating rules may be discovered and evaluated. The authors pursued two specific objectives. The first was to screen alternative rule formulations so that the more detailed evaluations using the CRM and CRIM models could be focused on the most likely candidates for change. The second objective was to compare three different collective choice rule sets for operating the River in the event of a severe, sustained drought.

A simplified simulation model of the Colorado River system (labeled with the acronym AZCOL) was constructed to facilitate the gaming exercises. AZCOL was developed specifically to expedite the gaming activities. Representation of the Basin hydrology, storage and diversion structures, and operating rules were derived from the CRM model developed by Harding *et al.* (1995). Economic benefits of both instream and offstream uses and salinity damages were taken from the work of Booker and Colby (1995) and from the CRIM model (Booker, 1995). Hardy's estimates (1995) were the source of the environmental impact indicators.

The interstate drought gaming exercise had one player representing each state and one representing the U.S. Secretary of the Interior. Each player was a member of the Severe Sustained Drought research team. Three games, each with alternative sets of policy options and information flows, were conducted. The first was done by electronic mail, while the other two were performed with the players gathered together with the computer. Three sets of rules were selected for evaluation. The rules were limited to those which were judged to be implementable without major action by the Congress or the federal courts. One set was the *status quo,* which represented the present understanding of the Law of the River. The second was designed to simulate the operation of a river basin commission. The commission would provide more objective and extensive information than decision makers now receive. The form of commission proposed would have limited powers and would require unanimous agreement on rule changes. In the third game, the players were permitted to "bank" unused water allotments and to sell or lease water between states. Unanimity was not required, but the Secretary of the Interior had veto power to safeguard against imposing significant third party and environmental costs.

In the last of the modeling studies "Mitigating Impacts of a Severe Sustained Drought on Colorado River Water Resources," Taiye B. Sangoyomi and Benjamin L. Harding employ hydrologic simulations to assess the hydrologic implications of several of the drought-coping responses developed in the interactive gaming exercises reported by Henderson and Lord (1995). Once again, they employ their hydrologic model called the Colorado River Network Model (CRM) reported by Harding *et al.* (1995). They examine three of the drought-coping responses which had the most significant effect on drought mitigation and compare hydrologic impacts with those resulting from using the current operating criteria. These coping responses were each analyzed as part of three policy scenarios. The inflow data set used was for the most severe sustained drought described by Tarboton (1995). In addition to the SSD-inflow hydrology, the authors also assessed the effects of drought-coping rules under assumed normal and wet hydrologic conditions. The analysis identified streamflows at several locations and considered reservoir contents, total annual depletion, hydropower generation, and salinity concentrations. The normal and wet hydrology simulations use 1000 years of synthetic streamflows developed from observed flow data.

Findings and Recommendations

In the concluding paper, "Managing the Colorado River in a Severe Sustained Drought: An Evaluation of Institutional Options," by William B. Lord, James F. Booker, Benjamin L. Harding, Douglas S. Kenney, and Robert A. Young, the findings, conclusions, and recommendations of the Phase II study are summarized. These findings, conclusions, and recommendations fall into three groups: those which pertain to the operating rules presently in effect; those pertaining to potential changes in existing rules; and those which pertain to the feasibility of making such changes via negotiation, litigation, or legislation.

Limitations and Need for Further Research

Because of the large geographic scale, the technical complexity of the problem, and the limited resources and time available to the research team, the results must be considered as partial and tentative. The choice of a hydrologic measure of drought ignores the broader geographic effects of inadequate precipitation. Due to resource limitations, the geographic coverage of environmental impacts were not as extensive as might be preferred. Economic measures of direct water demand were highly aggregated and based upon a few local study sites. An additional economic concern arises from the lack of attention to secondary economic impacts. The research team hopes to continue its unique collaboration and to refine and extend the study over the next several years.

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The participants in the present study wish to acknowledge the contributions of those who conceived and planned the project and to recognize the endeavors of the Phase 1 team in laying the groundwork for this continued effort. Professor Henry P. Caulfield of Colorado State University chaired the Arid and Semi-Arid Lands Directorate's planning for a major study of the nature, potential impacts and policy responses to a severe sustained drought. An interdisciplinary team of researchers from universities throughout the Colorado River Basin developed a two-phase plan, and the Man and the Biosphere Program supported the first phase of the work. The Phase I report provided initial analyses of tree ring evidence for severe sustained droughts in the southwest, and included studies of the hydrologic, water quality, legal, political and economic ramifications of coping with such droughts (Gregg and Getches. 1991). Contributors to the earlier report who were not participants in Phase II efforts reported in this issue were Dorothea M. Bradley, John A. Dracup, Frank Gregg, Pamela Hathaway, Donald R. Kendall, William E. Martin and Henry J. Vaux, Jr.

Professor L. Douglas James, then Director of the of Utah State University Water Research Laboratory, spearheaded the planning, conceptualization and proposal preparation that culminated in the Phase 2 effort reported in this issue, and served as Principal Investigator and Technical Coordinator for the first two years of the Project. Professor Henry Vaux, then Director of the University of California Water Resources Research Institute, and an active participant and contributor in the Phase 1 study, aided greatly in the early planning and fund-raising efforts. When Professor James took leave from Utah State University in September 1992, David S. Bowles became Director of the Utah Water Research Laboratory, and took over the administrative management for the remainder of Phase 2. At that same time, William B. Lord of the University of Arizona assumed the role of Technical Coordinator, succeeded in February 1993 by R. A. Young. The Powell Consortium, consisting of the Directors of the Water Resources Research Institutes of the Colorado River Basin, also have provided financial support, advice and encouragement throughout the conduct of the project. J. P. Matusak of the Metropolitan Water District of Southern California provided advice, information, and helpful comments throughout the study. Last but not least, William Werick of the Institute of Water Resources, Corps of Engineers, provided wise counsel to the program and facilitated our contacts with modeling experts.

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THE TREE-RING RECORD OF SEVERE SUSTAINED DROUGHT[1]

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ABSTRACT: Frequent and persistent droughts exacerbate the problems caused by the inherent scarcity of water in the semiarid to arid parts of the southwestern United States. The occurrence of drought is driven by climatic variability, which for years before about the beginning of the 20th century in the Southwest must be inferred from proxy records. As part of a multidisciplinary study of the potential hydrologic impact of severe sustained drought on the Colorado River, the physical basis and limitations of tree rings as indicators of severe sustained drought are reviewed, and tree-ring data are analyzed to delineate a "worst-case" drought scenario for the Upper Colorado River Basin (UCRB). Runs analysis of a 121-site tree-ring network, 1600-1962, identifies a four-year drought in the 1660s as the longest-duration large-scale drought in the Southwest in the recent tree-ring record. Longer tree-ring records suggest a much longer and more severe drought in 1579-1598. The regression estimate of the mean annual Colorado River flow for this period is 10.95 million acre-feet, or 81 percent of the long-term mean. The estimated flows for the 1500s should be used with caution in impact studies because sample size is small and some reconstructed values are extrapolations.
(KEY TERMS: meteorology/climatology; water resources planning; dendrohydrology; drought planning; Colorado River; time series analysis; tree rings; water supply.)

INTRODUCTION

Periods of short-term or prolonged deficiency in precipitation, generally known as droughts, are such common occurrences in global climatic regimes that it would be rare indeed to find a time when the earth was drought-free. Even so, drought is difficult to define in terms that apply to all circumstances. For example, Sastri *et al.* (1982) reported finding no fewer than 60 definitions of drought in the literature, based on the nature of water requirements and the time of need for plants and animals. Assessment of the probability in the Southwest is likely to become more urgent as the burgeoning population places increasing demand on both supplies and distribution systems and as changing climate possibly narrows the gap between water demand and available supply. Although droughts are related to changes in large-scale atmospheric circulation (Namias, 1955), the circumstances that result in extended periods of dry weather are neither clearly understood nor predictable. Until these parameters are more clearly defined, a logical approach to assessing the probability of drought is to examine climatological and hydrologic records.

Perhaps the best example of persistent or recurrent drought in the gaged hydrologic records of the southwestern United States is the 1950s, when precipitation and streamflow were consistently low in a band from southern California to Texas (Thomas, 1962). For information on droughts before the late 1800s, we are forced to rely on proxy indicators of climate. Commonly used indicators are stratified sediments in streams, lakes, and swamps; pollen profiles; layered ice cores; and tree rings (Hecht, 1985). Advantages of tree-ring data over other types of proxy data include accurate dating to the year, ease of collection and replication, and preservation of low-frequency and high-frequency variations.

The tree-ring record of drought history in the Southwest is examined in this paper as part of a multidisciplinary study of the potential hydrologic impacts of severe sustained drought (SSD) on the Colorado River. The objectives are (1) to discuss the physical basis and limitations of tree rings as indicators of hydrologic drought, (2) to delineate spatial and temporal characteristics of Southwest drought from tree-ring data, and (3) to supply the SSD project with a

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"worst-case" scenario for extreme hydrologic drought on the Colorado River. The primary source of tree-ring data for this scenario is a tree-ring reconstruction of annual flow of the Colorado River at Lees Ferry, Arizona, 1520-1961 (Stockton and Jacoby, 1976). We approach the tree-ring material in this paper with a widening time-window – covering studies based on relatively short but well-replicated data and then proceeding to the longer but spatially patchy tree-ring evidence. We first discuss physical and statistical points important to the interpretation of tree-ring records as indicators as hydrologic drought.

TREE RINGS AS INDICATORS OF SEVERE SUSTAINED DROUGHT

The discipline concerned with the use of tree rings for dating past events is known as *dendrochronology*. Two subdisciplines, *dendroclimatology* and *dendrohydrology*, have developed rapidly during recent years and involve the reconstruction of climatic and hydrologic events. This rapid development has been made possible by the evolution of high-speed computers capable of handling large amounts of data and by the application of sophisticated statistical methods for studying complex relationships between tree-ring variables and climatic or hydrologic parameters. A comprehensive review of the theory and methods of dendrohydrology can be found elsewhere (Loaiciga *et al.*, 1993). The following discussion is limited to aspects of dendrohydrology dealing with the delineation of severe sustained drought.

Tree-ring chronologies reflect the complex of climatic and environmental conditions at the sites where samples were taken. Although this complex includes nonclimatic influences such as insect infestations, fires, and logging, the desired climatic signals can be maximized by careful site selection. Maximum response to precipitation can best be obtained by sampling trees on relatively well-drained, dry sites, where low soil moisture is likely to be the main environmental factor limiting growth (Fritts, 1976).

Tree-ring series from properly selected sites are effective proxy indicators of hydrologic drought because precipitation and evapotranspiration are key variables in the water balances of the tree and the river basin (Figure 1). The physical principles of the system in which precipitation is transformed to river discharge are fairly well understood, although modeling the physical relationships is often difficult because of the complexity of the geology and surface characteristics of the watershed and uncertainty about the spatial distribution of precipitation. The biological system in which precipitation is transformed into ring-width variations is much more poorly understood, but the direction of the relationships is predictable for certain species and site-types. Cambial growth of drought-sensitive trees is frequently limited by low internal water-potential, which in turn is affected by soil moisture in the root-zone and evaporative demand of the atmosphere (Kozlowski, 1971). Weather conditions favoring decreased watershed runoff (low precipitation and high evapotranspiration) also favor decreased water potential in the tree. The empirical evidence for a relationship is significant correlation between tree-ring variables and hydrologic variables in diverse climatic regimes (Schulman, 1956; Smith and Stockton, 1981; Cook and Jacoby, 1983; Cleaveland and Stahle, 1989).

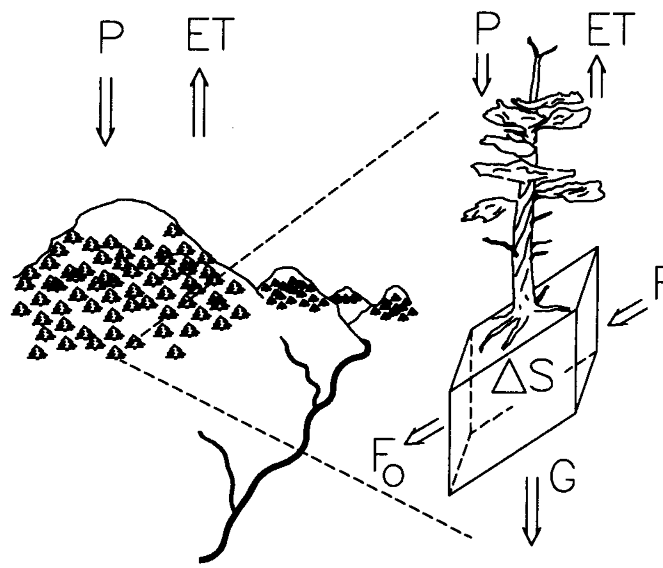

Figure 1. Sketch Illustrating Water-Balance Components Important in Tree-Ring Reconstruction of River Flow. Variables are precipitation (P), evapotranspiration (ET), surface and subsurface inflow and outflow (F_i and F_o), percolation to ground water (G), and change in soil moisture (ΔS).

Because snowmelt and precipitation in the cooler months are major contributors to streamflow in the West, the prospects for streamflow reconstruction would be bleak if winter moisture could not influence tree growth. The tree-growth response to precipitation is fortunately not limited to precipitation in the season of active cambial growth. Studies have consistently shown that tree-ring series from the semiarid Southwest are significantly correlated with precipitation in the cool months preceding the beginning of annual cambial growth (e.g., Schulman, 1956; Fritts, 1976; Smith and Stockton, 1981). One reason for the cool-season response is that soil moisture recharged during the winter is available for use by the tree at the beginning of the growing season. Moreover, a snowpack can extend this period of influence later into the spring. Another reason for a cool-season response is that biological processes important to the water and energy balances of the tree (e.g., photosynthesis, respiration, food storage) are not restricted to the cambial growing season but continue year-round.

Two statistical properties of tree-ring data that bear on the ability of reconstructions to identify and quantify SSD are "age trend" and autocorrelation. For typical drought-sensitive trees in open-growth stands, ring-width generally decreases with age of the tree after an initial period of juvenile growth. The decrease, which is at first steep and then more gradual, is at least partly a geometrical phenomenon: the crown stabilizes in growth, and a fairly constant annual wood increment is deposited on an increasingly large circumference. Biological changes associated with aging might also be expected to impart a gradual change in annual wood production over the life of the tree. The trend associated with the enlarging circumference and aging is a nonclimatic feature and must be mathematically removed before the tree-ring series can be used in hydrologic reconstruction.

The form of the mathematical curve used to detrend ring-width series varies widely with the study objectives and the site characteristics. For climatic studies, the general approach is to detrend conservatively to remove as little low-frequency climatic information as possible (Cook *et al.*, 1990). A modified negative exponential curve or straight line with negative slope has been found empirically to fit the age trend well for many ring-width series from open-growth sites in the semiarid western United States (Fritts, 1976). A consequence of detrending with monotonically decreasing curves such as these is that any real monotonic climatic trend covering the lifetime of the tree cannot be detected in the final tree-ring chronology. Information on shorter-wavelength climate variations – for example, reduced mean precipitation extending over several decades – will still be retained in the chronology.

Tree-ring series after detrending are often still positively autocorrelated (Meko *et al.*, 1993). Biologically-induced autocorrelation might be expected in tree rings because of carryover processes such as root dieback, multi-year needle retention, and food storage (Fritts, 1976). Likely consequences of autocorrelation are a lag in the response of tree growth to the transition from favorable moisture conditions to drought, and a lag in the recovery to normal growth after the end of a drought. Dendrochronologists frequently "prewhiten" – or mathematically remove the autocorrelation from – tree-ring data before using them in reconstructions in an effort to circumvent this problem (Meko and Graybill, 1995). Another approach is to include lagged tree-ring series as predictors in the reconstruction models (Stockton *et al.*, 1985). Neither approach probably completely reverses the distorting influence of the biological filtering of climate by the tree-growth system. Because the biological processes building autocorrelation into tree rings presumably operate similarly over the tree's lifetime, autocorrelation is perhaps less of a problem when reconstructions are used in a *relative* sense to compare properties of reconstructed droughts, rather than in an *absolute* sense to infer hydrologic statistics, such as the maximum number of consecutive years that river flow is below some specified threshold.

Most modern tree-ring reconstructions of hydrologic variables have been based on linear regression models (e.g., Cook and Jacoby, 1983; Cleaveland and Stahle, 1989; Meko and Graybill, 1995). The standard error of prediction, a calibration statistic, can be used to quantify the uncertainty in the reconstructed values, and validation on independent data can be used to guard against model overfitting (Meko and Graybill, 1995). Two factors must be considered, however, in judging the accuracy of the long-term reconstructions from calibration-period and verification-period statistics. First, the standard error of prediction does not apply for years in which the tree-ring data are outside the multivariate cloud of points defined by the predictor data for the calibration period (Weisberg, 1985). Reconstructed values for those years are classified as extrapolations rather than interpolations and should be flagged as such in reconstructions (e.g., Graumlich and Brubaker, 1986; Meko and Graybill, 1995). This is an important point since episodes of SSD identified in the reconstruction are likely to be based on extrapolations if the episodes are more severe than any droughts observed in the instrumental period. Second, reconstructed values in the earliest parts of a reconstruction might be more uncertain than those in the calibration and verification periods because the sample size (number of trees) of a tree-ring chronology typically decreases toward the beginning of the chronology (Meko and Graybill, 1995). Guidelines currently used to avoid noise amplification due to sample-size changes in building chronologies (Wigley *et al.*, 1984) were not available at the time many chronologies in existing tree-ring networks were developed.

In the application of tree rings to river-flow reconstruction, it should be recognized that tree-ring data are point samples, while river flow is a spatially integrated measure of moisture. Just as multiple rainfall gages are desirable in rainfall-runoff modeling, multiple tree-ring sites are desirable for river-flow reconstruction. Unlike rain-gage siting, however, tree-ring sampling must be opportunistic and must take into account the importance of site-type to the sensitivity of tree-growth to moisture variations. The opportunistic aspect of the problem is that trees with the desired properties (e.g., suitable species, great age, minimal influence by fire and disease) might not be available in the primary runoff-producing part of the basin. To complicate matters, the strongest precipitation signal in Southwestern conifers is frequently found not at higher elevations where most runoff originates but at the relatively dry lower forest border, where low soil moisture is more likely to be a major limiting factor to growth (Fritts, 1976). Tree-ring sampling for SSD studies in a river basin should include some sites in all major runoff-producing areas, or at least in nearby areas whose climatic variations closely parallel those of the runoff-producing areas.

DROUGHT HISTORY FROM RECENT TREE-RING RECORDS

Recent tree-ring records are defined here as those that extend no further back in time than about 1600 with acceptable sample replication. The period after 1600 is characterized by a rapid expansion in the spatial coverage of tree-ring chronologies in the western United States. The beginning of the 17th century is also a critical dividing point – as will be shown – because chronologies that do not extend to earlier years fail to sample a major drought at the end of the 16th century.

Analysis of spatial patterns of tree-growth for the period 1705-1979 from a network of 248 moisture-sensitive chronologies scattered over the coterminous United States indicates that the regional tree-ring signal for drought is especially strong in chronologies from the interior western United States (Meko *et al.*, 1993). Two of the nine U.S. tree-ring regions identified by Meko *et al.* (1993) are relevant to this study because they flank the Upper Colorado River Basin (UCRB) on the north and south. A region centered on south-central Montana includes a broad area from Idaho across Montana and Wyoming to the western edge of the Great Plains. The region includes the Wind River Mountains, which contribute runoff to the Green River tributary of the Colorado River. A region centered on Arizona includes all of Arizona and New Mexico, and southern parts of California, Nevada, Utah, and Colorado. The northern parts of the this region include several southern drainages of the UCRB.

The time-series plots of the two regional tree-growth series show little agreement in the timing of major low-growth anomalies in the far northern and southern parts of the interior western United States (Meko *et al.*, 1993 – Figure 12). The regional variability in timing of the most severe droughts as measured by moisture conditions averaged over several years is illustrated in a listing of the lowest 5-year, 10-year, and 20-year means for the Arizona and Montana regional tree-growth series and three regional hydrologic reconstructions from the interior western United States (Table 1). The hydrologic reconstructions have different periods of time coverage and represent (1) annual precipitation variations in northeastern Nevada, (2) annual streamflow variations of the Salt River, whose runoff comes mainly from east-central Arizona, and (3) annual streamflow variations of the upper Gila River, whose runoff comes mainly from southwestern New Mexico. The Salt River reconstruction is grouped here with the "recent" tree-ring records despite the 1580 starting date because the early years of record are based mainly on the juvenile growth portion of only a few tree-ring samples (Smith and Stockton, 1981).

Both the Arizona regional growth series and the Gila River reconstruction point to a period in the current century – the 1950s – as the most severe sustained drought in the tree-ring record. The lowest 20-year running mean centered on the 1950s for the Gila River was less than two-thirds the long-term mean annual flow. The same period is not, however, the record reconstructed low-flow period in terms of either 10-year or 20-year means on the Salt River, despite the small separation distance (less than about 100 km) between the main runoff-producing areas of the Salt River and upper Gila River. Such apparent inconsistencies might be explained by climatic or watershed differences. For example, the upper Gila watershed has a greater summer rainfall component than the watershed of the Salt River, and the Salt River is more strongly influenced by snowmelt. The tree-ring data summarized in Table 1 clearly point to a difficulty of identifying any one period of "most severe" sustained drought applicable to multiple basins in the Southwest in the years since 1600.

To summarize large-scale spatial aspects of drought in the southwestern United States for the period 1600-1962, we have assembled a 121-site network of moisture-sensitive chronologies and tabulated drought-related properties of the data by runs analysis (Salas *et al.*, 1980). We grouped the sites into 2° x 3° latitude-longitude grid cells and used the departures of growth themselves as indicators of "dendroclimatological drought." Species of dubious quality for drought information (e.g., *Pinus aristata* from high elevations) were excluded from the network.

TABLE 1. Driest 5-Year, 10-Year, and 20-Year Periods in Tree-Ring Reconstructions From the Interior Western United States.

Series	Period	Lowest Means[1] 5-Year	10-Year	20-Year
Arizona[2]	1705-1979	1879-1883	1773-1782	1946-1965
Montana[2]	1705-1979	1756-1760	1931-1940	1800-1819
NE Nevada[3]	1600-1982	1957-1961 (81)	1652-1661 (86)	1860-1879 (91)
Gila River[4]	1663-1985	1818-1822 (42)	1947-1956 (56)	1943-1962 (64)
Salt River[5]	1580-1979	1666-1670 (43)	1728-1737 (51)	1721-1740 (65)

[1]Beginning and ending years of lowest n-year means; for reconstructions, number in parentheses is n-year mean expressed as percentage of long-term mean.
[2]Regionally average tree-ring series centered on Arizona and Montana (Meko *et al.*, 1993).
[3]Reconstructed annual precipitation for Northeastern climatic division of Nevada (Smith, 1986).
[4]Reconstructed annual discharge of Upper Gila River, Arizona and New Mexico (Meko and Graybill, 1995).
[5]Reconstructed annual discharge of Salt River, Arizona (Smith and Stockton, 1981).

Cell-average series were computed by averaging chronologies within cells, and regional "West" and "Southwest" series were subsequently computed by averaging over cells. The two-step procedure avoids biasing the regional-average series toward dense clusters of sites. The tree-ring sites, cells, and regional boundaries are shown on the map in Figure 2. The "Southwest" region comprises the block of 20 cells bounded on the west approximately by the western border of Arizona; the "West" region comprises the remaining 15 cells. Seven of the 35 cells in the grid have no tree-ring sites, leaving a total of 28 active cells. Drought was defined to occur when a regional series dropped below its 0.2 quantile – the value exceeded in 80 percent of the years from 1600 to 1962.

Time series plots of the regional series are roughly parallel but differ markedly in some time periods (Figure 3). For example, drought hit the Southwest region but not the West region in 1902, 1904, and 1954-56; and hit the West region but not the Southwest region in the 1790s.

Following the terminology of runs analysis, a run of n consecutive years below the 0.2 quantile was defined as an "n-year drought," and the severity of the drought was measured by its run-sum: the sum of the deficits below the 0.2 quantile over the n years. The duration and severity of all multi-year droughts in the two regional series are listed in Table 2. The longest run in the current century was three years in both regions: 1954-1956 in the Southwest and 1959-1961 in the West. The longest run in the full-length series was four years (1667-1670) in the Southwest and six years (1843-1848) in the West.

Persistent droughts in the two regions were generally not synchronous. A simple tabulation of the number of droughts in each century in the Southwest region matched by droughts in the West region is shown below:

1600s	0	of	3
1700s	2	of	3
1800s	2	of	5
1900s	0	of	1

Any attempt to designate a particular drought as "most severe" is necessarily subjective because drought has many properties, all of which cannot be quantified by a single analytical method. Using runs analysis with the specified drought threshold on this particular data, the most severe sustained drought in the Southwest region for the time period 1600-1962 is 1667-1670. This drought had the largest run-length and run-sum. The 1660s drought has previously been noted as the lowest five-year running mean in the Salt River reconstruction (Table 1).

The most severe sustained drought is much less clearly defined in the West region. The longest drought, which occurred in the 1840s, did not have the largest run-sum:

Drought Years	Run Sums
1843-1848	0.49
1653-1655	0.62
1782-1783	0.50

Furthermore, drought assessment in the West region is extremely sensitive to the arbitrary level of drought threshold. If the threshold is relaxed slightly from the 0.2 quantile, for example, droughts of 1752-1754 and 1756-1757 merge into a single six-year drought from 1752 to 1757. A previous tree-ring reconstruction for the Sacramento River identified the

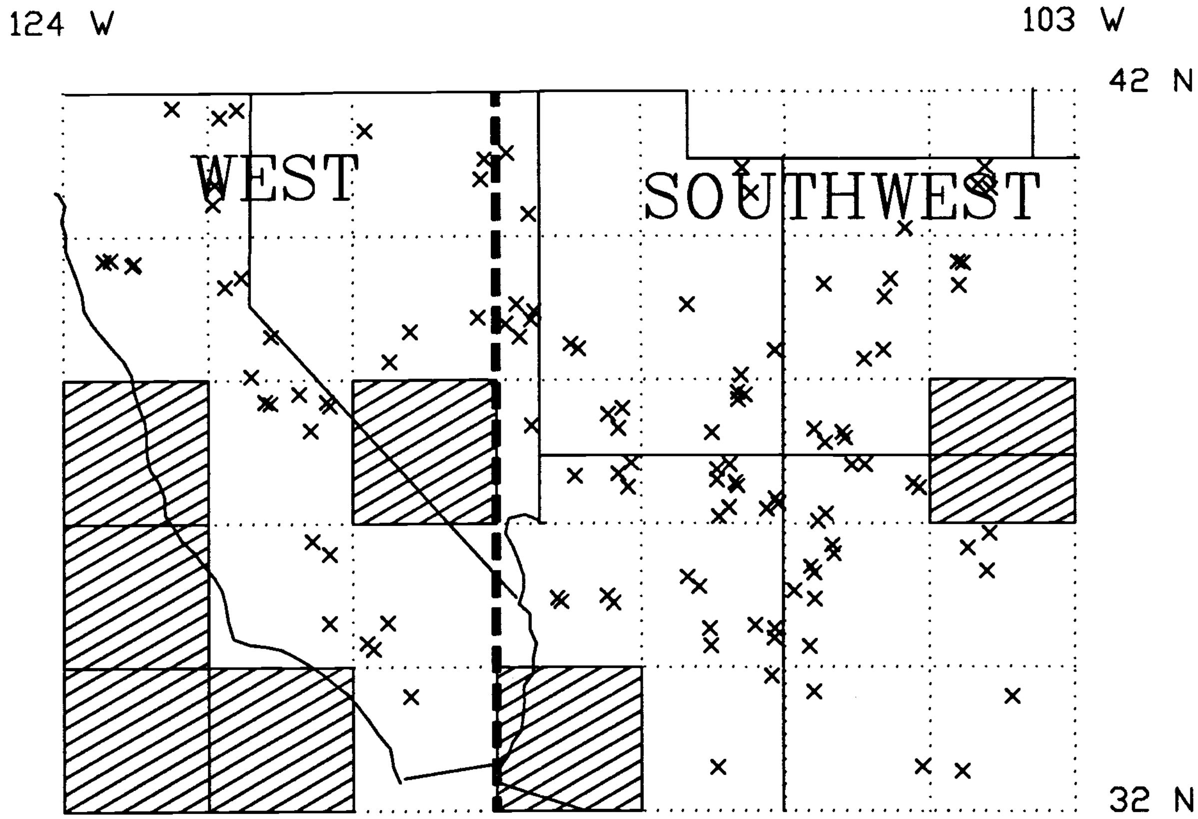

Figure 2. Map Showing Tree-Ring Sites Used in Grid-Cell Tabulation of "Dendroclimatological" Drought in West and Southwest Regions. Site locations are marked by "x," cell boundaries by dotted line, and boundary between West and Southwest regions by thick dashed line. Hatched cells contain no tree-ring sites.

1930s as the most severe low-flow period since AD 1560 and the 1840s as a period unique for drought duration (Earle and Fritts, 1986). Extreme drought severity in the 1840s has also been reported in a reconstruction of precipitation for central California (Michaelsen *et al.,* 1987).

DROUGHT HISTORY FROM LONG TREE-RING RECORDS

The available network of tree-ring sites in the western United States becomes sparse before 1600, but crude inferences about spatial patterns of drought are still possible. Fritts (1965) inferred changes in moisture conditions, 1501-1940, over western North America from contours of decadal-average growth departures over a 26-site network, and commented on severe drought conditions near the end of the 16th century:

– 1566-1585: Dry conditions intensify in the Southwest and northern Rockies; a major drought develops until it finally extends throughout the entire West.

– 1581-1605: Dry conditions become more restricted to the Rocky Mountain areas as moist conditions develop in the Rio Grande and Gila River Basins and in the Northwest.

Tree-ring information on drought becomes increasingly localized before 1500 as the network of available tree-ring sites becomes more sparse. On the Colorado Plateau, archaeological studies are a rich source of very long tree-ring chronologies. The archaeological history of the Southwest is a kaleidoscope of the rise and fall of ancient civilizations with the availability of water. Douglass (1935) concluded from an analysis of tree-ring data from living trees and archaeological wood samples from the Mesa Verde area that the most severe drought in the period 700-1930 occurred from 1276 to 1299. He named this period "The Great Drought," a term which has persisted through time. Although there is no unanimity of opinion, many archaeologists believe that this period of severe sustained drought resulted in the abandonment of large centers of Pueblo culture.

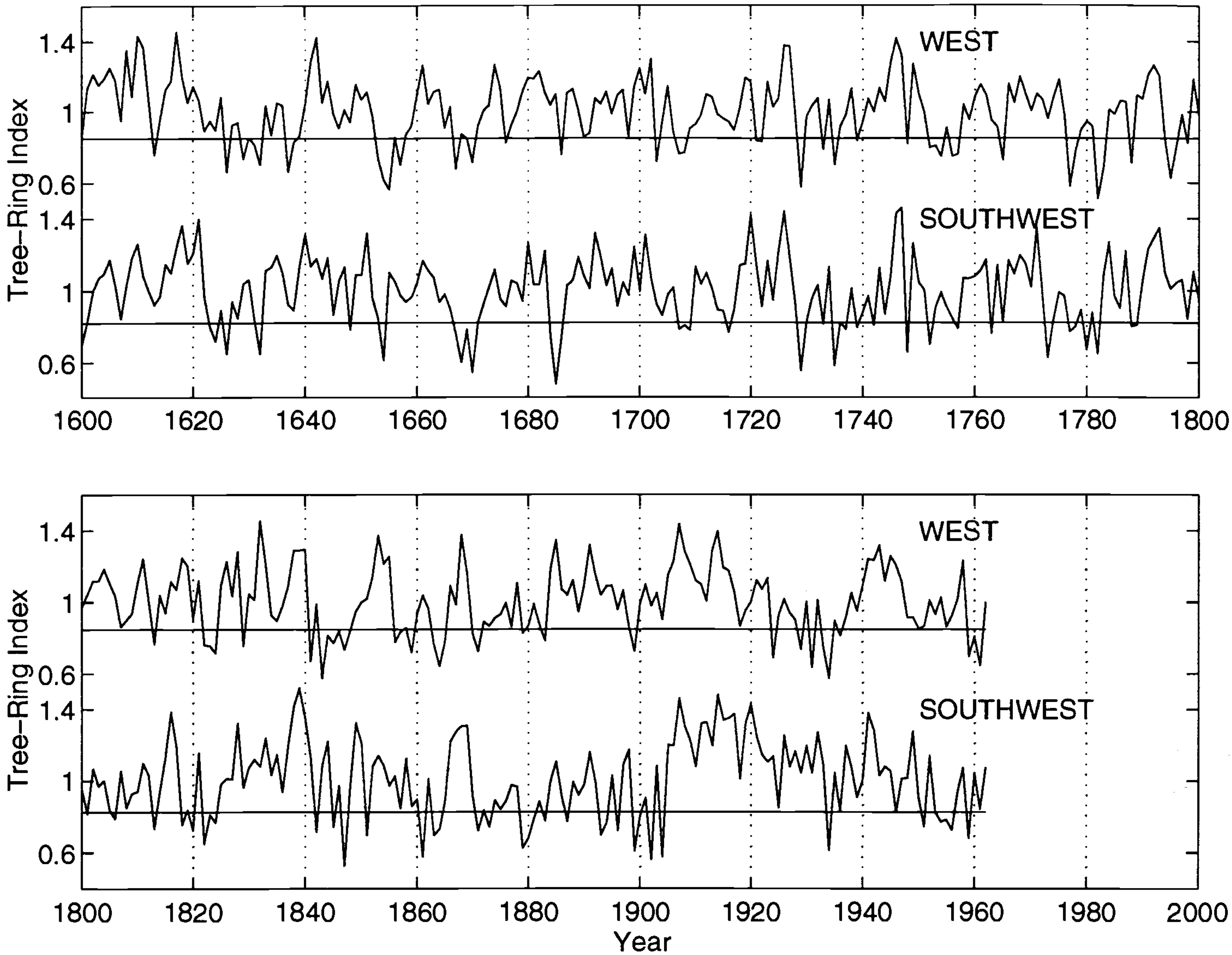

Figure 3. Regional-Average Tree-Ring Index for the West and Southwest Regions, AD 1600-1962. Y-axis indicates growth anomaly as fraction of normal growth (e.g., 1.0 is normal and 1.4 is 140 percent of normal). Horizontal line marks the 0.2 quantile – the index value exceeded 80 percent of the time.

Because of controversy concerning such climatic interpretations from tree-ring chronologies, Fritts *et al.* (1965) analyzed climate-tree growth relationships in the Mesa Verde area and made further climatic interpretations from an expanded tree-ring data base. The new results confirmed the existence of a "Great Drought" but placed it from 1273 through 1289. Although this was the most sustained dry period since 1273, several shorter but more severe droughts in terms of five-year means of tree-ring indices were identified between AD 512 and 1673.

Arroyo Hondo is another example of the importance of water availability to the development of ancient civilizations in the Southwest. Arroyo Hondo is a 14th-century pueblo at an elevation of 7,100 feet immediately west of the foothills of the Sangre de Cristo Mountains in north-central New Mexico. As part of a multidisciplinary study conducted by the School of American Research at Santa Fe, Rose *et al.* (1981) reconstructed the climate of the area by using tree-ring chronologies developed from living trees and archaeological material. Their work, along with other investigations, has made it possible to relate the development of Arroyo Hondo to climatic variations.

Arroyo Hondo was established around AD 1300 when precipitation was increasing after a 50-year period of below average years. Precipitation remained above the long-term mean for most of the first 35 years of settlement. The pueblo reached its maximum size during this period and was apparently one of the

TABLE 2. Regional Droughts Lasting Two or More Years as Identified by Runs Analysis.*

Southwest				West			
Start	End	N	Sum	Start	End	N	Sum
1623	1624	2	0.12	1631	1632	2	0.17
1667	1670	4	0.59	1627	1638	2	0.20
1684	1686	3	0.48	1653	1655	3	0.62
1707	1709	3	0.09	1707	1708	2	0.16
1777	1778	2	0.07	1721	1722	2	0.02
1788	1789	2	0.03	1752	1754	3	0.18
				1756	1757	2	0.18
				1777	1778	2	0.33
				1782	1783	2	0.50
				1794	1796	3	0.26
1822	1824	2	0.24	1822	1824	3	0.30
1863	1864	2	0.22	1843	1848	6	0.49
1879	1881	3	0.37	1856	1857	2	0.08
1893	1894	2	0.18	1863	1865	3	0.35
1899	1900	2	0.23	1870	1871	2	0.14
1954	1956	3	0.19	1933	1234	2	0.37
				1959	1961	3	0.38

*Summary based on time series, 1600-1962, plotted in Figure 3; headings defined in text.

largest communities in the area. Precipitation became quite variable around 1335, population began to decline, and the pueblo was virtually abandoned by 1345. After about 40 years of near-abandonment and coincident with another period of favorable precipitation, a second phase of settlement began. A new town was built on the ruins of the old, reaching maximum expansion in the early 1400s. Following a disastrous fire, the final occupation came to an end.

Rose *et al.* (1982) expanded the Arroyo Hondo work with tree-ring reconstructions of climatic variables for the southeastern Colorado Plateau and surrounding areas for the period 900-1970. Tree-ring records from archaeological samples and living trees were used in the analysis. The 20-year moving-average of reconstructed Palmer Drought Severity Index (PDSI) for the Northern Rio Grande climatic division, New Mexico, is plotted in Figure 4. A striking feature of the reconstruction is the relative severity of drought in the late 1500s in the context of the last thousand years. The lowest 20-year mean occurred in the period 1573-1592. During this time the average PDSI was below -2.0, which is classified as moderate drought in the PDSI system (Palmer, 1965). The same period contains seven consecutive years (1579-1585) of PDSI below -2.0. The next longest run of drought years is five, and the longest run in the period covered by instrumental data is four (1953-1956).

LATE-1500S DROUGHT IN THE UPPER COLORADO RIVER BASIN

The importance of the Colorado River as a source of water for agriculture, for hydroelectric power generation, and for municipal and industrial uses in the southwestern United States cannot be overstated. This 1,440-mile river flows through some of the most arid lands in the country, and its 244,000 square-mile drainage area includes parts of seven states and a small portion of Sonora and Baja California in Mexico. The Colorado has an average annual flow of just under 14 million acre feet (maf), much less than the Columbia and Mississippi Rivers. In spite of this relatively low flow, more water is diverted from the basin than from any other river basin in the United States. The river is an important source of supply for southern California and, with the Central Arizona Project, for the metropolitan areas of Phoenix and Tucson in Arizona.

The tree-ring history of drought in the UCRB is recorded in a reconstruction of annual flow of the Colorado River at Lees Ferry, Arizona, 1520-1961 (Stockton and Jacoby, 1976). The tree-ring collections for the study consisted of 30 different sites from the major runoff producing regions (Figure 5). These sites were selected primarily to sample the widely separate runoff-producing areas in the three major sub-basins – the Green River, the San Juan River, and the main stem of the Colorado River. Multivariate regression models were calibrated using linear functions of the

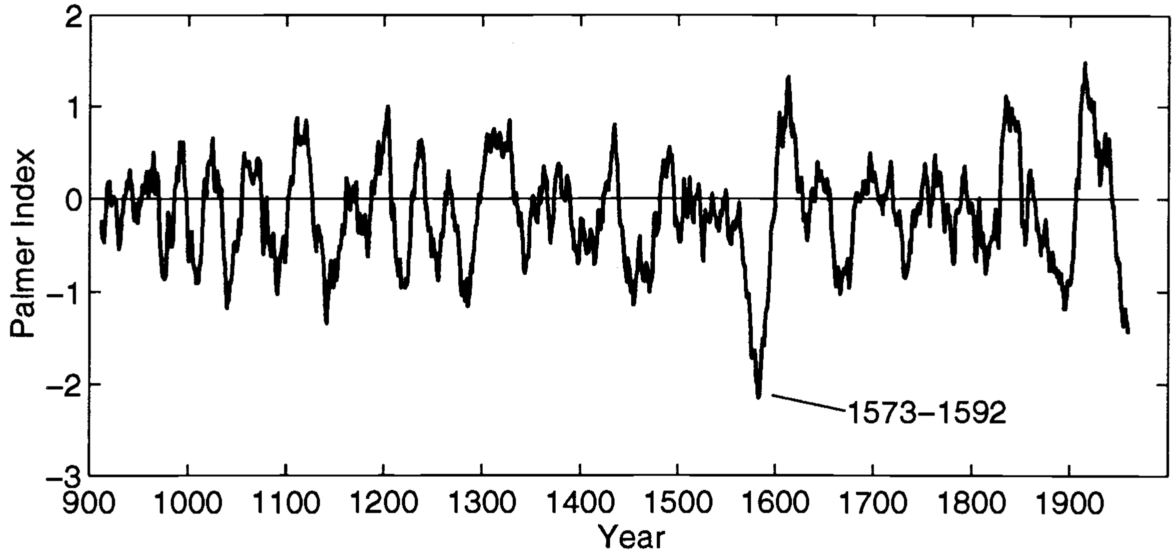

Figure 4. Twenty-Year Moving Average of Reconstructed July Palmer Drought Severity Index for the Northern Rio Grande Climatic Division, New Mexico (after Rose *et al.,* 1982). Values are plotted at mid-points of 20-year periods.

tree-ring data as predictors and the annual virgin flow record as the predictand. Various models were generated using different combinations of predictors, different model structures, and different versions of the virgin-flow record for calibration. The groups of chronologies used as predictors in the Lees Ferry reconstruction models are subsets of the sites marked in Figure 5. The groups include at least two chronologies from each of the major runoff-producing areas in Figure 5. The regression equations explained at least 75 percent of the variance of the observed flow in the calibration. Reconstructions from two of the more effective models were averaged to get the final reconstruction for the Colorado River at Lees Ferry, 1520-1961.

Stockton and Jacoby's (1976) reconstruction indicated that the estimated long-term mean annual flow of the Colorado River at Lees Ferry was only 13.5 maf – considerably less than the 16.2 maf annual flow estimated from gaged records early in this century and used as a basis for the Colorado River Compact. The reconstructed flow series also gives insight into the long-term history of SSD in the river basin. The time series of 20-year running means of the reconstruction contains several large-amplitude fluctuations on the order of 2 maf from the long-term mean (Figure 6).

If analysis of the series in Figure 6 is restricted to post-1600, the most severe sustained UCRB drought is centered in the 1660s, a period already identified in the Salt River reconstruction (Table 1) and the runs analysis (Table 2). Other low points in the smoothed Colorado River series also overlap

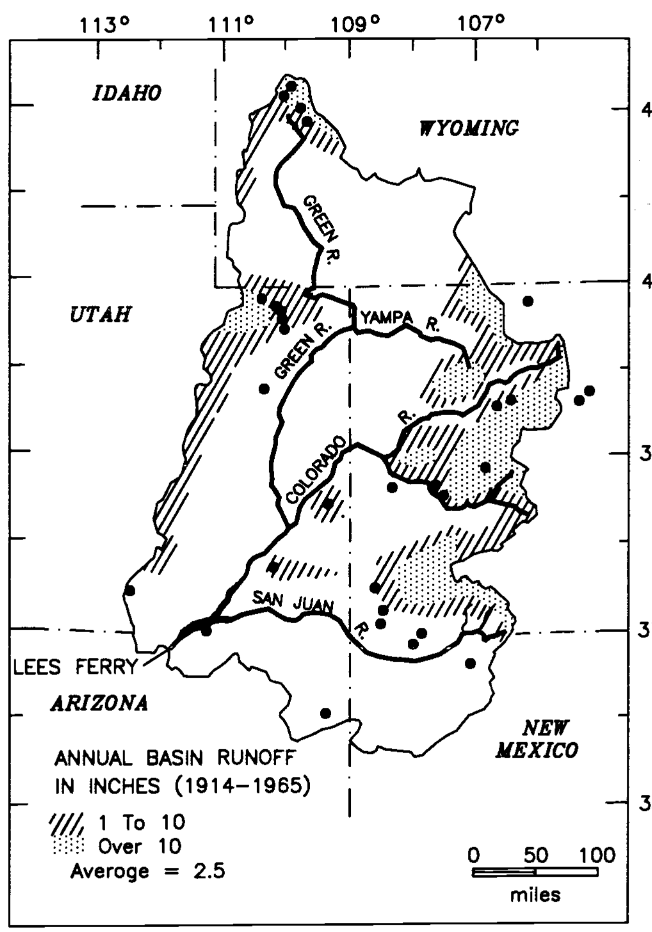

Figure 5. Map of Upper Colorado River Basin Showing Major Runoff-Producing (shaded), and Locations Tree-Ring Sites (dots), Used in a Reconstruction of Flow of the Colorado River at Lees Ferry, Arizona (after Stockton and Jacoby, 1976).

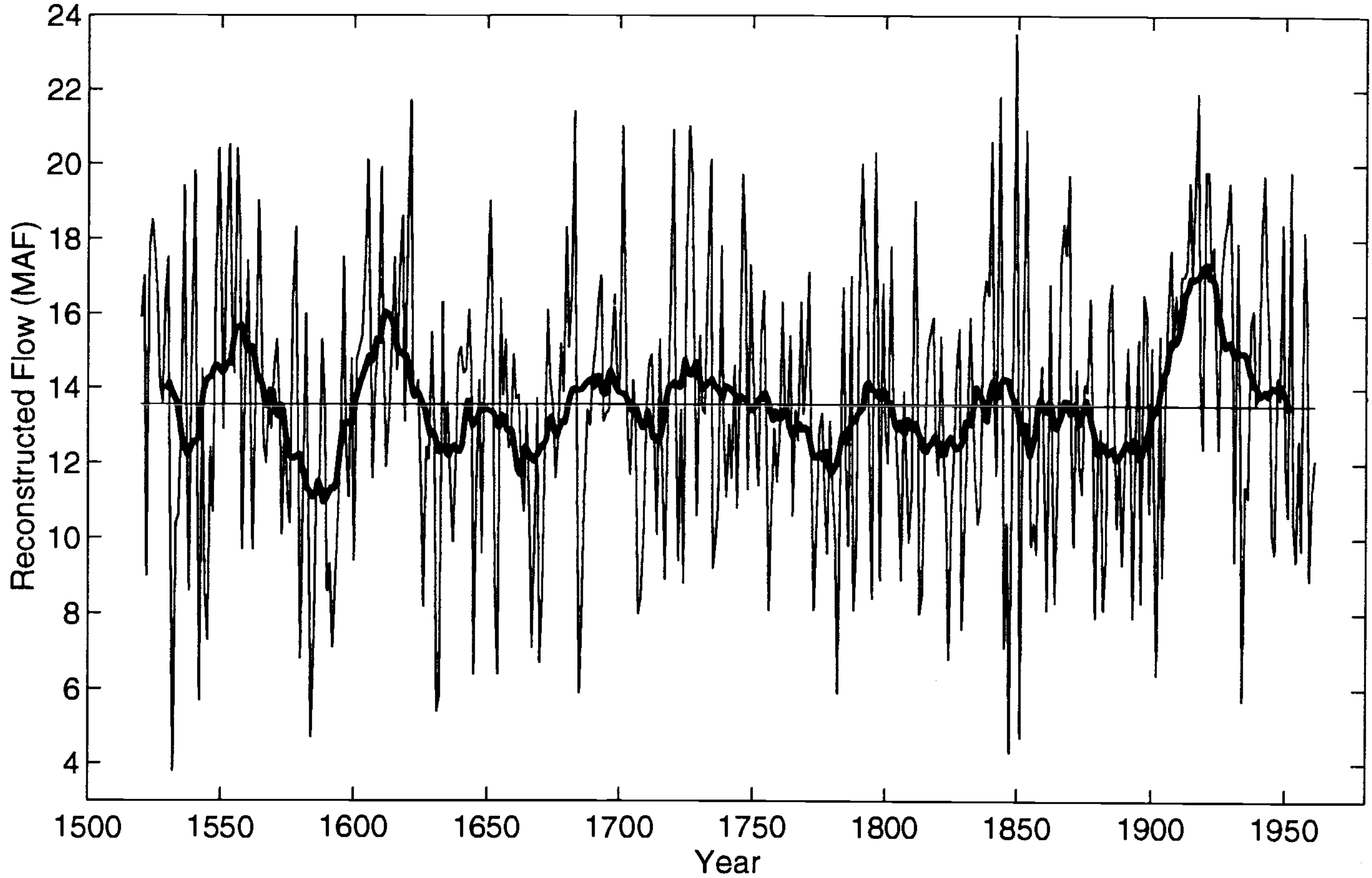

Figure 6. Annual Series and 20-Year Moving-Average of Reconstructed Flow of the Colorado River at Lees Ferry, Arizona. Units are million acre-feet (maf). Annual series covers 1520-1961. Moving-average series is plotted at midpoint of 20-year segment along x-axis (e.g., at 1910.5 for 1901-1920). Horizontal line marks long-term mean of annual series (13.5 maf). Source of data: Stockton and Jacoby (1976).

previously identified regional droughts – for example, the 20-year low in Montana tree growth (1800-1819) and the 10-year low in Arizona tree-growth (1773-1782).

The most interesting part of the Colorado River reconstruction occurs before 1600, when the smoothed series in Figure 6 dips to record lows. The ten lowest 20-year means all overlap the last decade of the 1500s. (Table 3). These 20-year means are much lower than at any other time in the reconstruction. The lowest is 10.95 maf, for the period 1579-1598. The late-1500s is also prominently represented in the list of ten lowest 5-year and 10-year running means.

Stockton and Jacoby (1976) commented on the 1500s drought in a assessment of time-series plots of tree-ring data from the UCRB:

> During the later part of the period from 1500 through 1600, an extensive drought occurred over most of the UCRB. All the tree-ring data series covering this time period show some evidence of this drought, but the magnitude and duration appear to vary in different parts of the Upper Basin. The longest and most severe drought appears to have occurred in the central portion of the UCRB (Upper Main Stem Area). The duration was somewhat reduced in both the northern and southern parts of the Upper Basin region.

Tree-ring records suggest that the drought of the late 1500s extended far beyond the boundaries of the UCRB. Evidence from the Upper Rio Grande Climatic Division, New Mexico, back to AD 900 has already been mentioned. Drought also apparently hit the Sacramento River Basin of California at about the same time. The reconstruction for the Sacramento River is slightly shorter than that for the Colorado River, extending back to 1560 (Earle and Fritts, 1986). The synchrony in time-series variations of reconstructed flow on the Colorado River and

TABLE 3. Lowest Reconstructed n-Year Means on the Colorado River (data after Stockton and Jacoby, 1976).

	5-Year		10-Year		20-Year	
Rank	Period	Flow (maf)	Period	Flow (maf)	Period	Flow (maf)
1	1590-1594	8.84	1584-1593	9.71	1579-1598	10.95
2	1583-1587	9.02	1583-1592	9.90	1580-1599	11.04
3	1667-1671	9.20	1585-1594	10.29	1575-1594	11.09
4	1589-1593	9.46	1663-1672	10.55	1576-1595	11.16
5	1531-1535	9.56	1773-1782	10.57	1581-1600	11.18
6	1591-1595	9.64	1662-1671	10.65	1574-1593	11.23
7	1666-1670	9.68	1579-1588	10.75	1573-1592	11.30
8	1542-1546	9.70	1582-1591	10.79	1583-1602	11.30
9	1541-1545	9.76	1580-1589	10.82	1578-1597	11.31
10	1580-1584	9.90	1586-1595	10.84	1582-1601	11.34

Sacramento River has been examined by Meko *et al.* (1991). Although the correlation coefficient between the two reconstructions is small (r=0.23, N=402 years), persistent drought sometimes occurred at the same time in the two basins. The extreme example of concurrent drought is the period 1579-1598 – the lowest 20-year mean on the Colorado River and the third lowest non-overlapping 20-year mean on the Sacramento River.

A map of the average tree-ring departures over the UCRB for the 1579-1598 period verifies that the drought was characterized by dry conditions in all major runoff-producing parts of the basin (Figure 7). For this analysis, 20-year running means were computed for each tree-ring chronology for the period 1520-1963; the 425 running means at each site were ranked in ascending order, and the percentile ranking of the 1579-1598 mean among the sample of 425 running means was computed. The 1579-1598 mean was below the 50th percentile (median) at all 18 tree-ring sites and was at the 6th percentile or lower at eight sites. At least one chronology in each of the major runoff-producing regions was at its 6th percentile or lower of growth during the drought. Driest conditions are inferred for the San Juan Basin and the headwaters of the main stem of the Colorado River.

We emphasize that streamflow reconstructions are estimates as opposed to measurements of past flow and that quantitative drought assessment from tree-ring studies should always be accompanied by an acknowledgment of uncertainty in the data. Uncertainty is common to all proxy indicators of climate. The expected error in reconstructions can vary greatly depending on the sensitivity of the tree-ring series to the hydrologic variable of interest. With a regression R^2 exceeding 0.75, the Colorado River reconstruction is a high-quality tree-ring reconstruction as measured

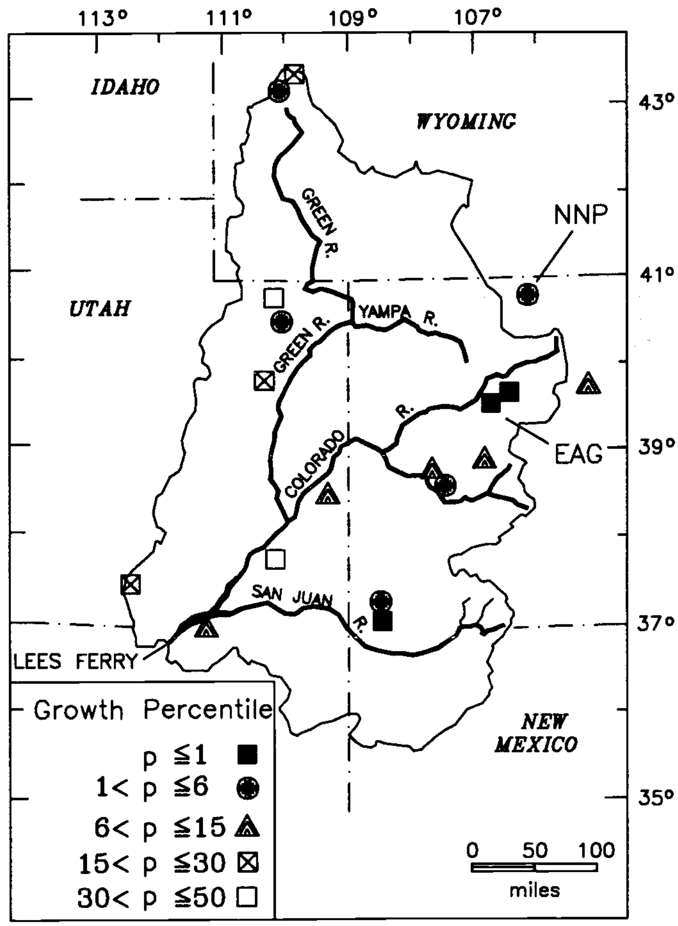

Figure 7. Spatial Pattern of 1579-1598 Tree-Growth Anomalies in the Upper Colorado River Basin. Symbols mark tree-ring anomalies at sites used by Stockton and Jacoby (1976) to reconstruct Colorado River flow at Lees Ferry, Arizona. Symbols are coded as percentile ranking of the 20-year-mean tree-ring index for 1579-1598 among all 20-year running means for the period 1520-1963. Labels "NNP" and "EAG" refer to sites mentioned in text.

by calibration statistics. Because of the shortness of the overlap period of the gaged-flow record and the tree-ring record, the regression model was not verified rigorously on independent data. The possibility that the calibration R^2 is inflated due to overfitting of the model cannot therefore be ruled out. Comparison of reconstructed values with a recent U.S. Bureau of Reclamation version of the natural-flow series based on gaged data indicates that, for the post-1905 period, the mean absolute error of the annual estimates is 1.7 maf and the standard deviation of the errors is 2.0 maf. It is reasonable to expect somewhat smaller errors in n-year means. For example, a simple regression of 10-year running means of the natural flow series against the reconstructed flow yields a standard deviation of errors of 0.46 maf. As mentioned previously, however, calibration-period statistics do not apply to regression estimates classified as extrapolations, and many of the extremely low reconstructed annual values in the late 1500s are probably extrapolations.

The reconstruction error in the 1500s could possibly be greater than suggested by regression statistics because of the drop in sample size (number of trees) in the early parts of the chronologies. The worst case for the 18 sites used in the reconstruction equations is New North Park, Colorado (NNP in Figure 7). The sample size at NNP drops from 21 cores in 1900 to one core in 1590. At the other extreme is the Eagle, Colorado, site (EAG in Figure 7), which has a sample size of 21 cores in 1900 and 19 cores in 1590. That this well-replicated chronology is one of three chronologies in its lowest percentile of growth in the late-1500s drought argues in favor of the reality of the reconstructed drought. Sample-size changes for the other chronologies are much less drastic than for NNP but are still substantial. For the 18 sites, the median ratio of the number of cores in 1900 to the number in 1590 is 2.6.

CONCLUSION

Tree-ring studies with varying time coverage and spatial resolution contribute to our knowledge of the history of severe sustained drought in the Southwest. Periods delineated as most severe sustained drought differ from basin to basin and region to region over the Southwest, as might be expected from the spatial variability of precipitation anomalies.

Although tree-ring coverage becomes spotty before 1600, evidence strongly points to a period in the late 1500s as a period of drought much more severe and prolonged than any drought in succeeding years. Tree-rings indicate that multi-decadal drought in the late 1500s simultaneously hit widely separate locations: the northern part of the Rio Grande drainage in New Mexico, the Colorado Rockies, and the drainage of the Sacramento River in the Sierra Nevada Mountains of California.

The term "most severe sustained drought" makes sense only in the light of a specific time-frame, geographic focus, and summary variable. As recommended in the June 8-9, 1989, meeting of the Severe Sustained Drought group in Boulder, Colorado, we have addressed the time-frame reliably sampled by tree-ring data, focused on the interior Southwest – especially the Upper Colorado River Basin – and adopted the 20-year moving average of reconstructed annual flow as the drought variable. Shorter droughts of great intensity may of course cause hardship in some parts of the study area, particularly those not tied in to distribution facilities of major water supply entities. A moderate prolonged shortage in precipitation over a period of 20 years or longer, however, could possibly stress water supplies even for systems with multiple years of reservoir storage, such as the Colorado River.

The most severe sustained drought in the tree-ring record for the UCRB occurred in 1579-1598. The tree-ring estimate of the severity of this drought as measured by 20-year-average flow is period is 10.95 maf, or 2.55 maf below the long-term reconstructed mean of 13.5 maf. We emphasize that the error in the reconstructed values of Colorado River flow for the 1500s might be considerably larger than suggested by regression statistics because some extremely low flows are probably extrapolations rather than predictions and because the number of trees in the early part of the chronologies is small. The uncertainty of the 1500s reconstructed values could possibly be reduced by building up the sample sizes of chronologies with additional collections of very old trees.

Tree-ring reconstructions are useful in the absence of other data in placing rough bounds on the expected variability of parameters such as the frequency, intensity, and duration of drought. Future climatic change could alter the framework within which reconstructions are interpreted. Consideration of climatic change, as might for example result from greenhouse warming, is beyond the scope of this paper. Natural climatic variability alone, however, is sufficiently large to pose possible problems for future water supply in the semi-arid regions of the southwestern United States.

ACKNOWLEDGMENTS

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HYDROLOGIC SCENARIOS FOR SEVERE SUSTAINED DROUGHT IN THE SOUTHWESTERN UNITED STATES[1]

David G. Tarboton[2]

ABSTRACT: This paper considers the risk of drought and develops drought scenarios for use in the study of severe sustained drought in the Southwestern United States. The focus is on the Colorado River Basin and regions to which Colorado River water is exported, especially southern California, which depends on water from the Colorado River. Drought scenarios are developed using estimates of unimpaired historic streamflow as well as reconstructions of streamflow based on tree ring widths. Drought scenarios in the Colorado River Basin are defined on the basis of annual flow at Lees Ferry. The risk, in terms of return period, of the drought scenarios developed, is assessed using stochastic models.
(KEY TERMS: drought; streamflow; Colorado River; hydrology; water resources management.)

INTRODUCTION

The inherent scarcity of water in the semi-arid to arid regions of the southwestern United States (Figure 1) is exacerbated by the occurrence of frequent and persistent droughts (Stockton *et al.*, 1991). The impact of these droughts is constantly changing as the growing population places increased demands on supplies. This is countered by the development of storage and distribution systems that can store water for up to decades and transport water thousands of miles. These measures provide security against local shortages of short duration but effectively interlink large regions. However, these large interlinked storage and distribution systems are now susceptible to sustained regional shortages of water supply.

This paper summarizes the hydrology work done as part of a multi-disciplinary study to assess the likely impacts of severe sustained drought in the region served by the Colorado River. It is a precis of the key results presented at greater length by Tarboton (1994). Figure 1 is a schematic of the study area. Most of the streamflow in the Colorado River comes from snowmelt in the Rocky Mountains in Colorado, Utah, and Wyoming. Several reservoirs, the largest of which are Lake Powell and Lake Mead, provide storage, hydroelectric power, and flood control. The use of water from the Colorado River is strictly controlled and governed by a complex system of law centered on the Colorado River compact. This apportions use of water between the upper and lower basins of the Colorado River basin. Use of water is apportioned among states by other compacts and court decrees. Some of the water supply systems for utilization of this water are indicated in Figure 1. Southern California – in particular the metropolitan area surrounding Los Angeles – draws water from the Colorado River via the Colorado River aqueduct, as well as from northern California. This paper focuses only on streamflow in the Colorado River. For drought impacts on southern California, the possibility of simultaneous shortage in the Colorado River and northern California is considered by Tarboton (1994).

In this paper critical periods of shortage in the historic and paleo (tree ring) streamflow record are identified. These are used to develop study scenarios. Stochastic techniques were used to characterize the spatial distribution of supply during these scenarios and to assess the risk or likelihood of occurrence of these scenarios.

The sources of data upon which this paper was based consisted of the following unimpaired streamflow estimates and streamflow reconstructed from the measurement of tree-ring widths:

1. Historic unimpaired streamflow at 29 sites in the Colorado River basin, 1906-1983 (78 years), as estimated by the U.S. Bureau of Reclamation.

[1]Paper No. 95040 of the *Water Resources Bulletin*. **Discussions are open until June 1, 1996.**
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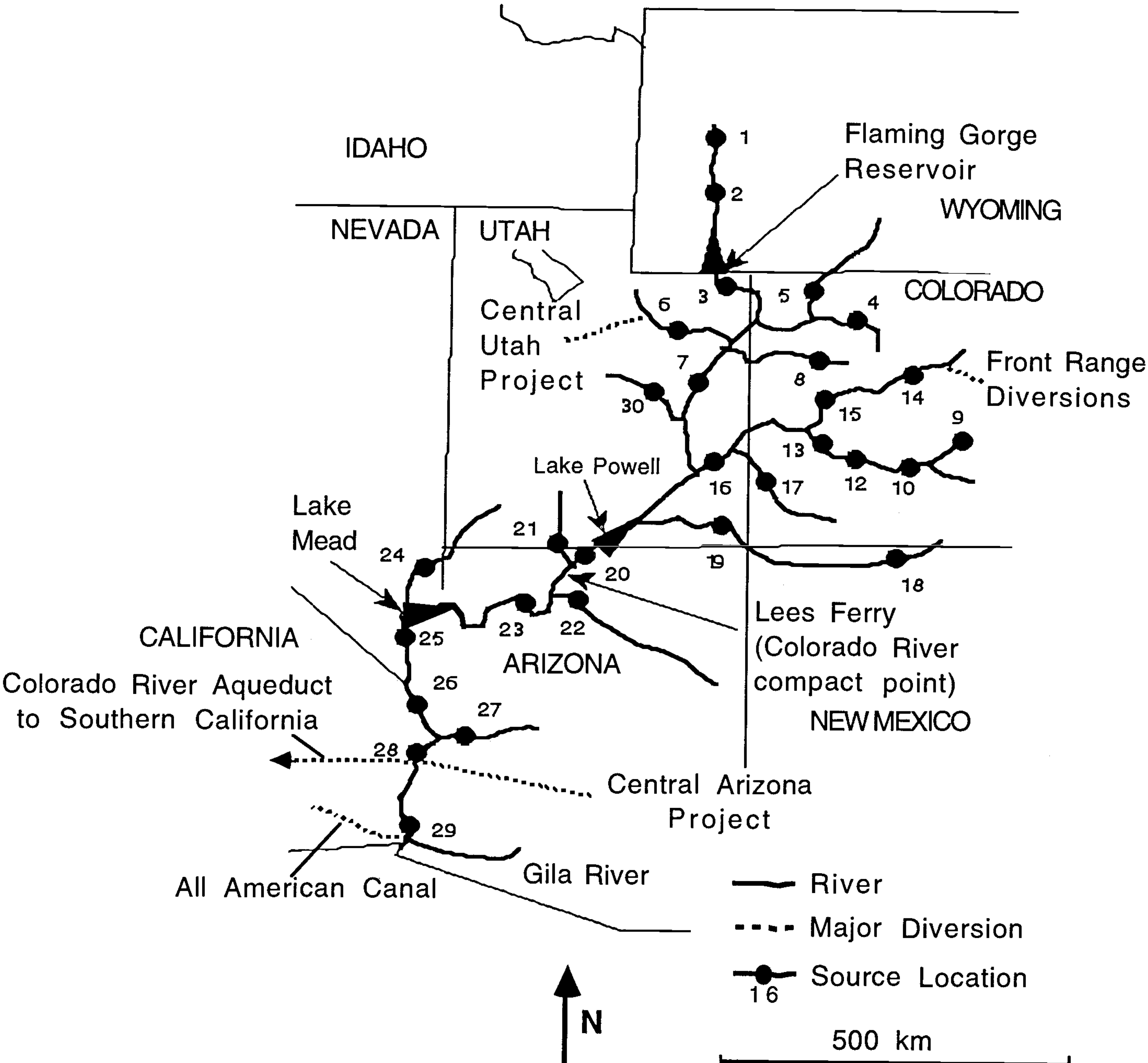

Figure 1. Southwestern United States Study Area Showing the River and Water Distribution Systems Involved. Numbered points are the source inflow locations used by the Colorado River simulation model.

2. Tree-ring reconstructed streamflow at Lees Ferry on the Colorado River, 1520-1961 (442 years), from Stockton and Jacoby (1976).

3. Tree-ring reconstructed streamflow at Lees Ferry on the Colorado River, 1568-1962 (395 years), from Michaelson *et al.* (1990).

Streamflow at Lees Ferry is used in this paper to refer to streamflow at the Colorado River compact point near Lees Ferry, Arizona, defined as a point one mile downstream of the confluence of the Colorado and Paria Rivers. This is the sum of streamflow measured at the Lees Ferry gage upstream of the Paria confluence and the Paria gage. The compact point legally subdivides the Colorado River basin into upper and lower basins.

Unimpaired streamflow is measured streamflow adjusted for anthropogenic consumptive use and reservoir operations. It is an estimate of what streamflow would have been had the basins remained in their natural state.

Tree-ring studies offer a physical basis for the extension of hydrologic records further back than observed records, and thus they provide a window into the past that may yield additional information on the possible magnitude and frequency of the occurrence of droughts. These record extensions do not suffer from the uncertainty associated with stochastically generated sequences, but they do contain uncertainty associated with the relationship between tree ring widths and streamflows. Despite these drawbacks, tree rings often provide the only physically realistic glimpse of past hydrologic conditions which could recur and should be planned for. The approach in this work was to take advantage of the information provided by tree-ring reconstructions of streamflow to identify and develop severe drought scenarios. To allay skepticism regarding the use of tree ring reconstructed streamflow, one drought scenario based only on recorded streamflow was used.

Figures 2, 3, and 4 compare observed and tree-ring reconstructions of streamflow in the Colorado River at Lees Ferry. The Colorado River streamflow reconstructions are regarded in the tree-ring literature as adequate (Michaelson *et al.*, 1990; Stockton and Jacoby, 1976). The cross correlation (see, for example, Benjamin and Cornell, 1970, p. 15, Equation 1.3.2) between observed and reconstructed streamflow is 0.76 for the Stockton and Jacoby reconstruction and 0.77 for the Michaelson *et al.*, reconstruction. Table 1 gives statistics of the observed and reconstructed streamflow series. Notice that since the reconstructed streamflow is obtained from regression of tree ring width indices against the observed streamflow, the unexplained variance is omitted, resulting in smaller standard deviations in the reconstructed as compared to observed streamflow.

One feature of the Lees Ferry reconstruction is an apparent difference in the mean over the period of recorded flows (15.2 million acre-feet, MAF) from that of the reconstructed flows (13.5 MAF) (see Figure 3). [The units used for streamflow are either million acre-feet (MAF) per year or thousand acre-feet (KAF) per year; 1 acre-foot is 1.23 x 10^3 m^3.] A t test indicates that this difference is significant ($t > 3$, $p < 0.004$). This apparent nonstationarity is of concern because the methods for reconstruction of streamflow from tree-ring indices include detrending (removing nonstationarity) from tree-ring indices before correlation with streamflow. This feature is apparent in both Lees Ferry reconstructions.

The differences between the two Colorado River reconstructions are disturbing and could have a significant impact on planning strategies. The ten-year moving averages (Figure 4) sometimes differ by as much as 2 MAF between the two reconstructions when compared to a mean of 13.5 MAF. This occurs immediately after a sustained severe drought from 1600 to 1630 and could be important for recovery of the system. It also occurs from 1800 to 1830 where one reconstruction is in a drought and the other in surplus. However, differences such as these are

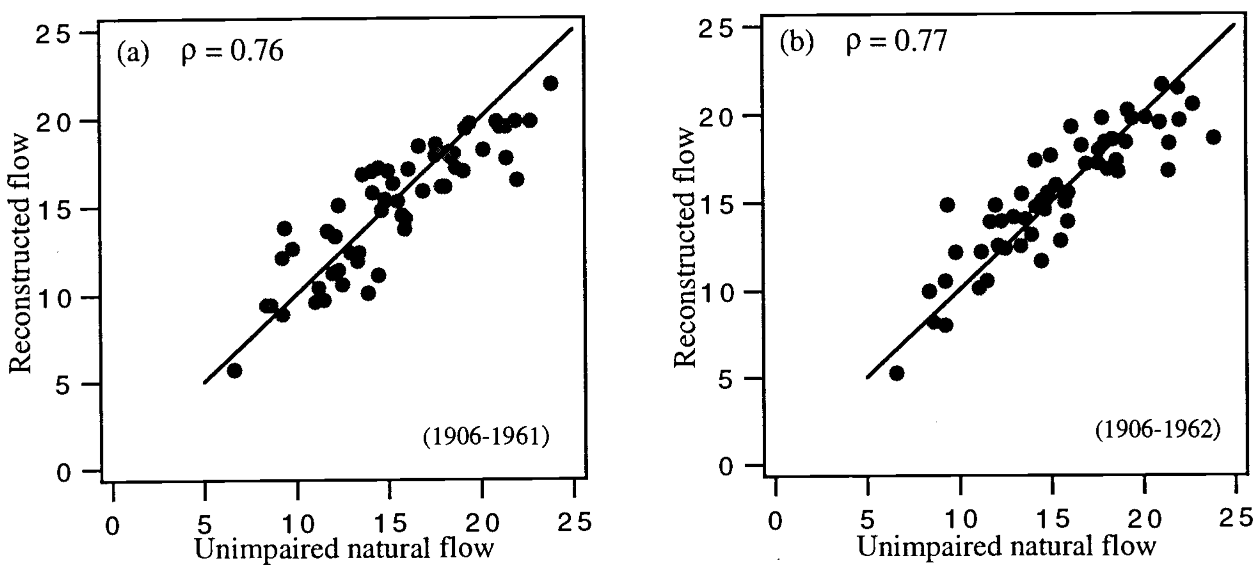

Figure 2. Comparison of Observed and Tree-Ring Reconstructed Annual Streamflow in Million Acre Feet (MAF): (a) Lees Ferry Reconstruction (Stockton and Jacoby, 1976); (b) Lees Ferry Reconstruction (Michaelson *et al.*, 1990). The solid line is a 1:1 line and ρ indicates cross correlation coefficient.

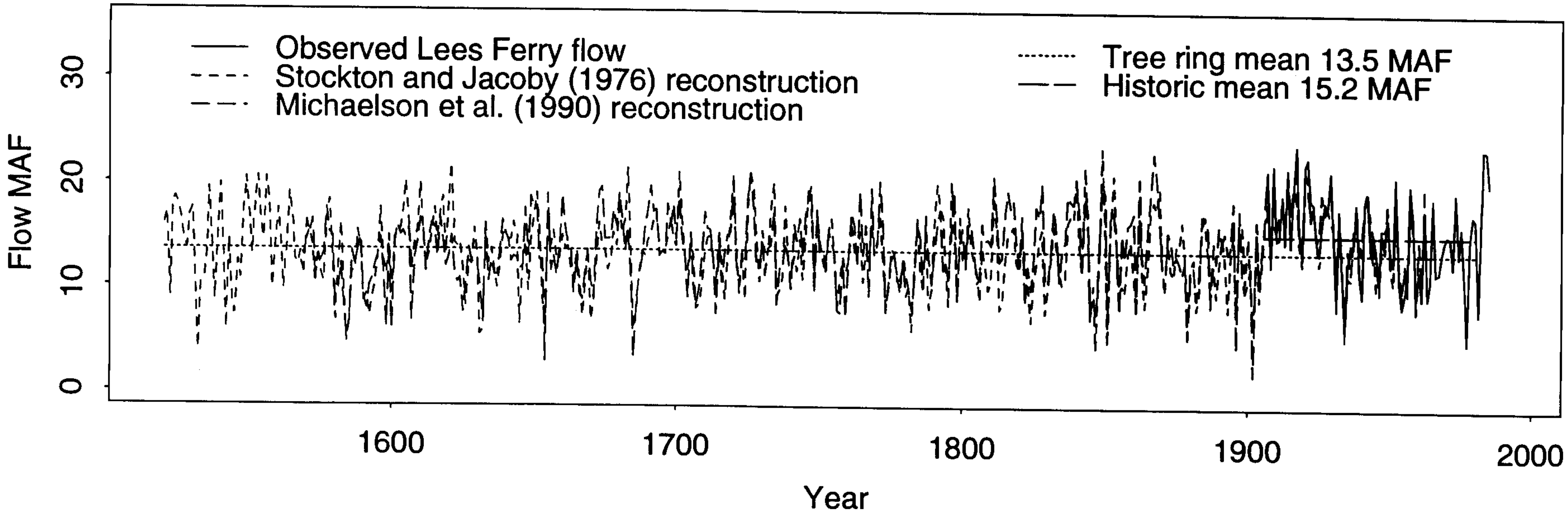

Figure 3. Time Series of Historic and Reconstructed Streamflow at Lees Ferry.

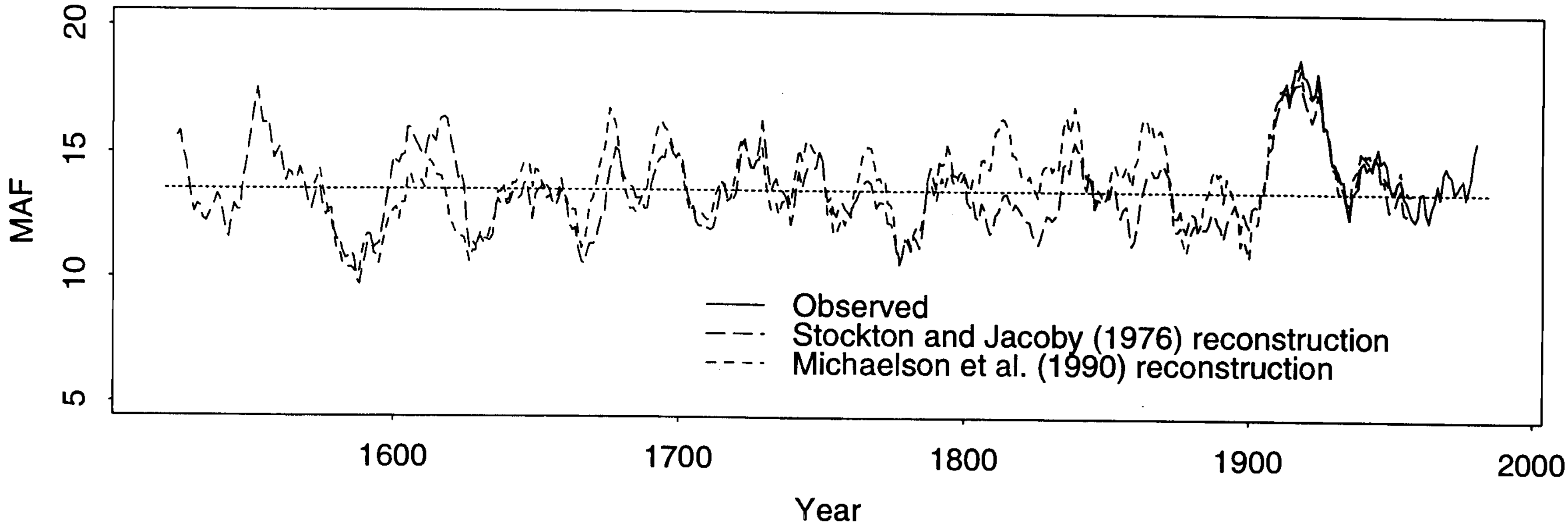

Figure 4. Ten-Year Moving Average of Historic and Reconstructed Streamflow at Lees Ferry.

TABLE 1. Statistics of Streamflow Series.

Series	Length (years)	Mean (MAF)*	Standard Deviation (MAF)	Annual Lag 1 Correlation	Hurst Coefficient
Unimpaired Flows at Lees Ferry 1906 to 1985	80	15.2	4.24	0.21**	0.73
Stockton and Jacoby (1976) Lees Ferry Reconstruction	442	13.5	3.59	0.32	0.63
Michaelson *et al.* (1991), Lees Ferry Reconstruction	395	13.8	3.61	0.26	0.65

*MAF (million acre-feet) = acre feet x 10^6 = 1.2^3 x 10.9 m^3.
**This correlation is not statistically different from 0 at the 95 percent confidence level.

reportedly typical statistical discrepancies in these type of tree-ring studies (Loaiciga *et al.,* 1992; Loaiciga *et al.,* 1993).

In the remainder of this article we used the Stockton and Jacoby (1976) reconstruction, for reasons detailed in Tarboton (1994).

IDENTIFICATION OF DROUGHTS AND DROUGHT SCENARIOS

Several options are available for the identification of severe sustained droughts in a flow record. Some of these are:

1. The drought with the maximum deficit magnitude (largest accumulated deficit below the mean annual flow over a continuous period with flow below the mean).
2. The drought that would cause the greatest reservoir depletion in a storage deficit analysis with fixed demand.
3. Visual inspection.

Figure 5 illustrates the application of these procedures to streamflow in the Colorado River at Lees Ferry. In the first option a drought is defined as a consecutive series of years during which the average annual streamflow is continuously below some specified threshold level, which is typically taken to be the long term mean (Dracup *et al.,* 1980; Yevjevich, 1967; Kendall and Dracup, 1991a). These periods are termed hydrologic droughts. A hydrologic drought can be defined by the following three attributes: (1) duration (L); (2) deficit magnitude (M) (the cumulative deficit below the threshold); and (3) deficit intensity [the average deficit below the threshold (M/L)]. A drawback of this procedure is that it classifies separately droughts that occur in quick succession separated by a single wet year (greater than the mean flow) that is insufficient to fill reservoirs.

Option (2), storage deficit analysis [also referred to as the sequent peak procedure (Kendall and Dracup, 1991b)] is a procedure whereby the storage deficit in a hypothetical semi-infinite reservoir initially full (zero deficit) is computed. Change in deficit is calculated each year by using a constant yield (taken to include outflow as well as evaporation) minus the inflow. If the deficit ever becomes negative, the excess is assumed to spill and deficit is reduced to zero. The maximum deficit is the storage capacity theoretically required to support the specified outflow or yield. In Figure 5d the yield was taken as 98 percent of the mean annual reconstructed streamflow (13.26 MAF), to reflect a high level of development. This high utilization is what is projected for the Colorado River in the year 2020 and is best for identification of sustained critical periods. An advantage of this analysis is that it gives an idea of the time required for a highly developed system with large storage to recover from a drought. Two or more droughts separated by a few wet years will still appear as critical in this analysis, if the intervening wet years are insufficient for the system to fully recover. As represented here, this is simply a drought identification tool and only very roughly represents what may happen to reservoir storage during a severe sustained drought. In times of severe drought the demand is elastic, and as deficits increase the demand will start to be curtailed as a variety of legal, institutional, social, and economic mechanisms governing water use during drought come into effect. Subsequent papers in this volume consider these issues.

Considering all of this information, the most critical period in the Colorado River basin were the years from 1579-1600, which contained three hydrologic droughts in quick succession (Figure 5b) and represented the most rapid increase in deficit (Figure 5d.). By comparison the largest deficit in Figure 5d accumulates over 150 years, too long a period to consider as a single drought event for this study. However, this does indicate that as the demand approaches

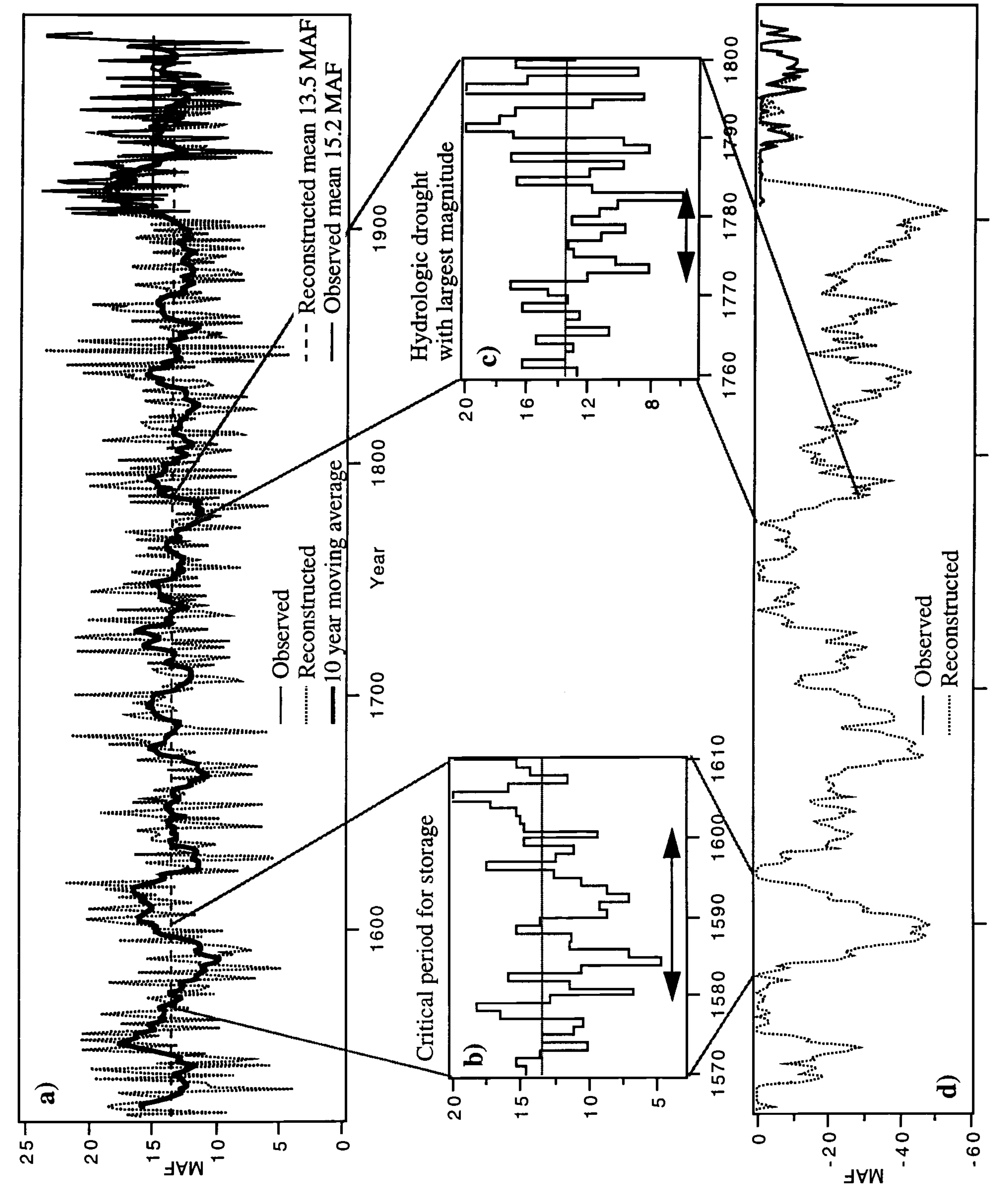

Figure 5. Colorado River at Lees Ferry Drought Identification: a) Streamflow, Annual, and Ten-Year Moving Average; b) Critical Period for Storage; c) Hydrologic Drought With Largest Deficit Magnitude; and d) Storage Deficit With Annual Yield of 13.26 MAF (98 percent of tree-ring reconstruction mean).

the mean flow, very long (150 year) periods with no surplus are possible.

The following drought scenarios were identified and used in this study:

1. **Colorado Drought of Historic Record.** The drought of 1943 to 1964 in the historic unimpaired streamflow record. This is defensible as likely to recur, not withstanding any doubt surrounding the reliability of the tree ring reconstructions.

2. **Colorado Severe Drought.** The Colorado River drought of 1579 to 1600 as reconstructed from tree rings.

3. **Colorado Rearranged Severe Drought.** The Colorado River drought of 1579 to 1600 with annual flows re-arranged to be in descending order in this period. This makes the same amount of water available as in scenario 1, but the extremely low flows are clustered together at the end, when reservoirs are already low or dry. This scenario is somewhat artificial but was included to explore how the system would respond to a truly catastrophic drought. This drought is illustrated in Figure 6. Also shown is the recovery period following the drought, comprising reconstructed streamflow for the years 1601 to 1616. The flows shown here from 1579 to 1616 comprise the 37-year analysis period used by accompanying papers in this volume.

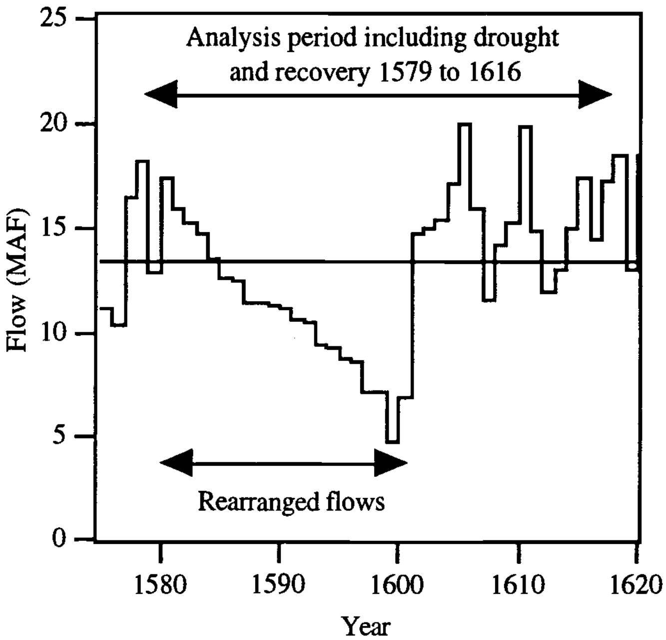

Figure 6. Colorado River Re-arranged Severe Drought and Recovery Period.

One goal of this project was to focus on the geographic impact of drought and the ability of the water management infrastructure and institutions to equitably and efficiently distribute the water that is available. This requires knowledge of the spatial distribution of water for the drought scenarios studied. Models of the water demand and allocation systems, such as the Colorado River Simulation System and California Department of Water Resources model, require monthly inputs at spatially distributed source points. Flows reconstructed from tree rings are aggregate values representing the sum of flows from all sites and seasons. To use these flows for drought planning requires that they be disaggregated into flows at each source site for each season (month). Procedures that are well documented and researched (Bras and Rodriguez-Iturbe, 1985; Grygier and Stedinger, 1988; Loucks *et al.*, 1981; Salas *et al.*, 1980; Stedinger *et al.*, 1985; Stedinger and Vogel, 1984) are available for disaggregation of annual basin aggregate flow into monthly flow at each site.

Here, disaggregation procedures were applied to drought scenarios 2 and 3 developed above. The disaggregation package SPIGOT (Grygier and Stedinger, 1988, 1990a, 1990b) modified to work off tree-ring reconstructed records, rather than annual flows generated from an autoregressive order, one model was used. Details of the implementation and testing of this approach are given in Tarboton (1994). The results provide reasonable estimates of possible spatial configurations of a drought scenario that has been defined by an aggregate Lees Ferry flow, and have been used in the impact analysis described in accompanying papers (Harding *et al.*, 1995; Sangoyomi and Harding, 1995). Drought scenario 1 was in the historic record, and its spatial configuration was already known. Estimated historic unimpaired flows at source locations were used in the study of this scenario.

QUANTIFICATION OF DROUGHT PROBABILITY FOR THE STUDY SCENARIOS

The probability or risk of the drought scenarios developed is required so that planners can be aware of the likelihood of the scenarios studied or similar scenarios actually occurring. Here statistical techniques are used to assess this probability. The evidence from geophysical data is that nature is continually changing with cycles of variability that stretch across years, decades, and even millennia. The assumption that has to be made in quantifying the risk associated with future droughts is that the past is an indicator of the future. One has to assume stationarity and hope that the observed variability of the data about an average is large when compared to the long-term shifts in that average value. This cannot be verified. Models that account for this uncertainty, such as models 3 and 4 below, allow us to hedge our bets. However any planning that makes use of this information needs to recognize the inherent uncertainty in planning for the future.

The basic statistics of the streamflow series studied were given in Table 1. The lag 1 correlation for historic unimpaired flows at Lees Ferry is not significantly different from 0 at the 95 percent confidence level under a statistical hypothesis test based on the variance of the sample correlation (Bras and Rodriguez-Iturbe, 1985, p. 57). This is not a very powerful test due to the shortness of the record, but it could be used to argue against using models with any sort of dependence between annual flows.

The Hurst coefficient has been estimated through rescaled range analysis (Pegram *et al.*, 1980; Bras and Rodriguez-Iturbe, 1985; Feder 1988). Range is defined as the maximum minus minimum cumulative departure from the mean in a sequence of flows n years long. Rescaled range is range divided by standard deviation. The Hurst coefficient is defined as the scaling exponent associated with the increase in rescaled range with sample size. It is recognized that given the length of record this is a highly uncertain statistic.

The likelihood of the drought scenarios developed was evaluated using four models for annual streamflow:

Model 1. Independent annual flows.

Model 2. Autoregressive order one model with fixed parameters.

Model 3. Autoregressive order one model, allowing for parameter uncertainty.

Model 4. Fractional Gaussian noise model using the estimated Hurst coefficient.

These cover the range of models that may be considered reasonable to simulate annual streamflow. The details of these models are given by Tarboton (1994). Model 1 could be justified in terms of the annual lag 1 correlation coefficient (Table 1) not being significantly different from zero. Model 2 (see for example Bras and Rodriguez-Iturbe, 1985) is popular in hydrology. Model 3 accounts for parameter uncertainty by using methods given by Grygier and Stedinger (1990a). Model 4 uses the successive random addition procedure (Voss, 1985; Feder, 1988) to generate Fractional Gaussian noise that approximates long memory and self similarity in the streamflow series.

Drought Scenario Characteristics

The extremely severe drought in the Colorado River from 1579 to 1600 was characterized by a sharp drop in the storage deficits because the 17-year mean streamflow (1579 to 1595) is 10.47 MAF, and the 22-year mean streamflow (1579 to 1600) is 11.05 MAF, both figures being considerably less than the historic mean of 15.2 MAF (1906-1983) and tree-ring reconstruction mean of 13.5 MAF (1520-1961). The Colorado rearranged severe drought (see Figure 6) consists of 16 years with below mean streamflow and is characterized by a 16-year mean of 9.57 MAF.

The basis for assessment of the likelihood of these scenarios was to compute the probability and return period of mean flows below these thresholds for each of the models considered. The approach taken here is different from that of Loaiciga *et al.* (1992, 1993), who used renewal theory to analyze hydrologic drought (sequences of years with streamflow below a threshold). Here droughts are characterized by a mean streamflow below a threshold. This approach is more appropriate where there is large storage, such as in the reservoirs on the Colorado River. A single slightly-above-threshold wet year does not replenish storage and end drought.

Return Periods for Multi-Year Drought Scenarios

Statistically the concept of return period, or recurrence interval, is well understood when talking about instantaneous occurrences. However, care is needed when the occurrences of interest (droughts) are of significant length. In terms of instantaneous occurrences, if the probability of an event in a unit time period is P, the return period is 1/P, measured in unit time periods. Now consider a multiple year event, such as an N year drought. Denote the probability of any N year period being such a drought as P_N. The return period measured in N year intervals is $1/P_N$, or measured in years is $R = N/P_N$. The probability of any one year being in an N year drought is $N/R = P_N$. Note that since P_N is a probability (less than 1) it is impossible to have R less than N, the duration of the drought being considered.

Table 2 summarizes calculations of return period R for each of the drought scenarios developed, using each of the annual streamflow models considered. Table 2 also includes a naive return period estimate, defined as the length of record from which the scenario was taken. Since these scenarios are the most critical in a historic or reconstructed record, this provides a simple estimate of return period. Models 1 and 2 can be solved analytically, so the results given are exact. Models 3 and 4 were solved by Monte Carlo techniques, simulating 10,000 years of streamflow and dividing 10,000 by the number of occurrences of droughts with N year mean less than the N year mean that characterizes the drought under consideration. Details of these calculations are given in Tarboton (1994).

In evaluating the results in Table 2, one needs to bear in mind that the return periods reported are for multiple year events. The probability of any one year selected at random being in that scenario is the scenario duration divided by return period. For example, if the return period of a 20-year duration event is 80 years, the probability of any one year selected at random falling within this drought event is 0.25, rather larger than the commonly perceived risk associated with an 80-year return period event. The scenarios studied, except for the rearranged severe drought, came from either the observed or tree-ring reconstructed historic record.

The historic record drought in the Colorado (1943-1964) is from an 80-year record, and the naive return period estimate of 80 years agrees well with model 3 and model 4 calculations. Models 1 and 2, which either do not reproduce correlation or assume parameters are perfectly estimated, seem to overestimate this return period. This is consistent with the lack of memory in these models. The streamflow mean used to characterize the historic record drought is only just less than the Stockton and Jacoby (1976) reconstruction mean. This explains why return periods only slightly longer than the drought scenario itself are obtained from model estimates based on fits to the tree-ring reconstruction. The severe drought in the Colorado (1579-1600) is from a tree-ring streamflow reconstruction 442 years long. Again the naive return period estimate of 442 years compares well with models 3 and 4, but models 1 and 2 estimate significantly longer return periods.

Overall it can be concluded that models 1 and 2 are biased in their estimate of return period, due to not considering parameter uncertainty and correlation in the case of model 1. Models 3 and 4 give comparable results, bearing out the idea that the Hurst phenomenon which was reproduced by model 4 is equivalent to uncertainty in the underlying process

TABLE 2. Colorado River Drought Return Period Estimates.

	Drought of Historic Record (1943-1964) Scenario 1	**Reconstructed Severe Drought (1579-1600) Scenario 2**	**Re-Arranged Severe Drought of 1579-1600 Scenario 3**
Characterizing Flow Mean (MAF*)	**13.43**	**10.47 or** 11.05**	**9.57**
Duration (years)	**22**	**17 or** 22**	**16**
	Return Period (years)	**Return Period (years)**	**Return Period (years)**
Naive	80	442	
Models Fitted to Unimpaired Historic Flows			
Model 1	970	9.9×10^6	3.6×10^8
Model 2	422	2.2×10^5	3.4×10^6
Model 3	107	5,000	> 10,000
Model 4	83	645	2000
Models fitted to Stockton and Jacoby (1976) Tree-Ring Reconstruction of Streamflow			
Model 1	49	38,000	3.3×10^6
Model 2	47	2,500	29,000
Model 3	32	555	4,000
Model 4	32	526	2857

*MAF (million acre-feet) = acre feet x 10^6 = 1.23×10^9 m^3.

**The reconstructed severe drought can be characterized by either a 17-year mean of 10.47 MAF or a 22-year mean of 11.05 MAF. The smaller return period (and corresponding higher probability) associated with these is reported here, because flow below either of these constitutes the drought scenario.

Note: Model 1. Independent Annual Flow; Model 2. Autoregressive Order 1 With Fixed Parameters; Model 3. Autoregressive Order 1 With Uncertain Parameters; and Model 4. Fractional Gaussian Noise. Once model parameters are estimated using either the historic unimpaired or tree-ring reconstructed streamflow, they are used to estimate return period for drought scenarios derived from both historic unimpaired and tree-ring constructed streamflow.

parameters and possible nonstationarity of these parameters that cannot be resolved given the amount of data available. Risk assessment is based primarily on models 3 and 4. The following are proposed as reasonable estimates of the range of uncertainty associated with the return period of each scenario:

1. Colorado Drought in Historic Record (1943-1964): 50 to 100 years.
2. Colorado Severe Drought (1579-1600): 400 to 700 years.
3. Colorado Rearranged Severe Drought: 2000 to 10,000 years or more.

The ranges reflect uncertainty in these estimates. We believe that given the information at hand, it is not possible to meaningfully reduce these ranges. Scenario 1 is therefore a once-in-a-lifetime type of occurrence, scenario 2 occurs less frequently, and scenario 3 is extremely rare or even unrealistic. Nevertheless, scenario 3 was the most interesting to analyze in the context of water shortages since it resulted in Lake Powell being drawn down to dead level. The subsequent papers focus most of their analysis on this scenario. This has been the basis for some criticism of the overall approach. However, this scenario could be viewed as a "probable extreme drought," and its analysis is still useful in focusing on the consequences of severe sustained drought. It is a testament to the reliability of water resources systems in the Colorado River basin that it takes a drought such as scenario 3 before any really extreme consequences are felt.

CONCLUSIONS

Drought scenarios have been developed for the study of severe sustained drought in the Colorado River basin. These scenarios were based on estimated unimpaired and tree-ring reconstructed streamflow. Some discrepancies between different streamflow reconstructions were noted. A variety of stochastic models including independent, autoregressive order one, and fractional Gaussian noise were used to estimate the return period and risk associated with the drought scenarios developed. These occurrence risks should be borne in mind when evaluating and developing planning strategies based on these scenarios.

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IMPACTS OF A SEVERE SUSTAINED DROUGHT ON COLORADO RIVER WATER RESOURCES[1]

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ABSTRACT: The impacts of a severe sustained drought on Colorado River system water resources were investigated by simulating the physical and institutional constraints within the Colorado River Basin and testing the response of the system to different hydrologic scenarios. Simulations using Hydrosphere's Colorado River Model compared a 38-year severe sustained drought derived from 500 years of reconstructed streamflows for the Colorado River basin with a 38-year streamflow trace extracted from the recent historic record. The impacts of the severe drought on streamflows, water allocation, storage, hydropower generation, and salinity were assessed. Estimated deliveries to consumptive uses in the Upper Basin states of Colorado, Utah, Wyoming, New Mexico, and northern Arizona were heavily affected by the severe drought, while the Lower Basin states of California, Nevada, and Arizona suffered only slight shortages. Upper Basin reservoirs and streamflows were also more heavily affected than those in the Lower Basin by the severe drought. System-wide, total hydropower generation was 84 percent less in the drought scenario than in the historical streamflow scenario. Annual, flow-weighted salinity below Lake Mead exceeded 1200 ppm for six years during the deepest portion of the severe drought. The salinity levels in the historical hydrology scenario never exceeded 1100 ppm.
(KEY TERMS: water resources planning; water policy/regulation/decision making; water management; water law; social and political; irrigation; water quality; simulation; drought.)

INTRODUCTION

In the Colorado River Basin, as in other arid areas of the globe, drought is a frequent phenomenon. Because droughts affect human activities, particularly food and energy production, a variety of measures to cope with droughts have been developed. In the Colorado River Basin, the most conspicuous drought-coping mechanism has been the construction of a complex of reservoirs with an aggregate storage capacity four times the average natural flow of the river. Thus frequent droughts, like those recorded since non-native settlement of the basin, are mitigated by delivery of water held in storage. The system has not been tested by an infrequent severe sustained drought.

Reconstructions of pre-historic streamflows in the basin, based on tree-ring analysis, show that droughts with much more severity than those indicated from historical streamflow records have occurred in the basin's past (Tarboton, 1995). In addition, should global warming occur, it will likely bring more variable precipitation, increased evapotranspiration, and possibly sustained droughts. Hence it is appropriate that, even though severe sustained droughts can be expected to occur infrequently, their effects be quantified.

The objective of this study was to investigate the impacts of such a severe and sustained drought on the hydrologic environment of the Colorado River Basin. The impacts were characterized in terms of streamflows, consumptive use, storage, hydropower generation, and salinity. The effects of the severe drought on these system characteristics were determined with a simulation model of the basin, the Colorado River Model.

PHYSICAL SETTING

The Colorado River basin drains approximately 243,000 square miles contained within the states of Colorado, Wyoming, Utah, New Mexico, Nevada, Arizona, California, and parts of the Mexican states of Baja, California, and Sonora (Figure 1). The basin is divided both geographically and politically at Lee

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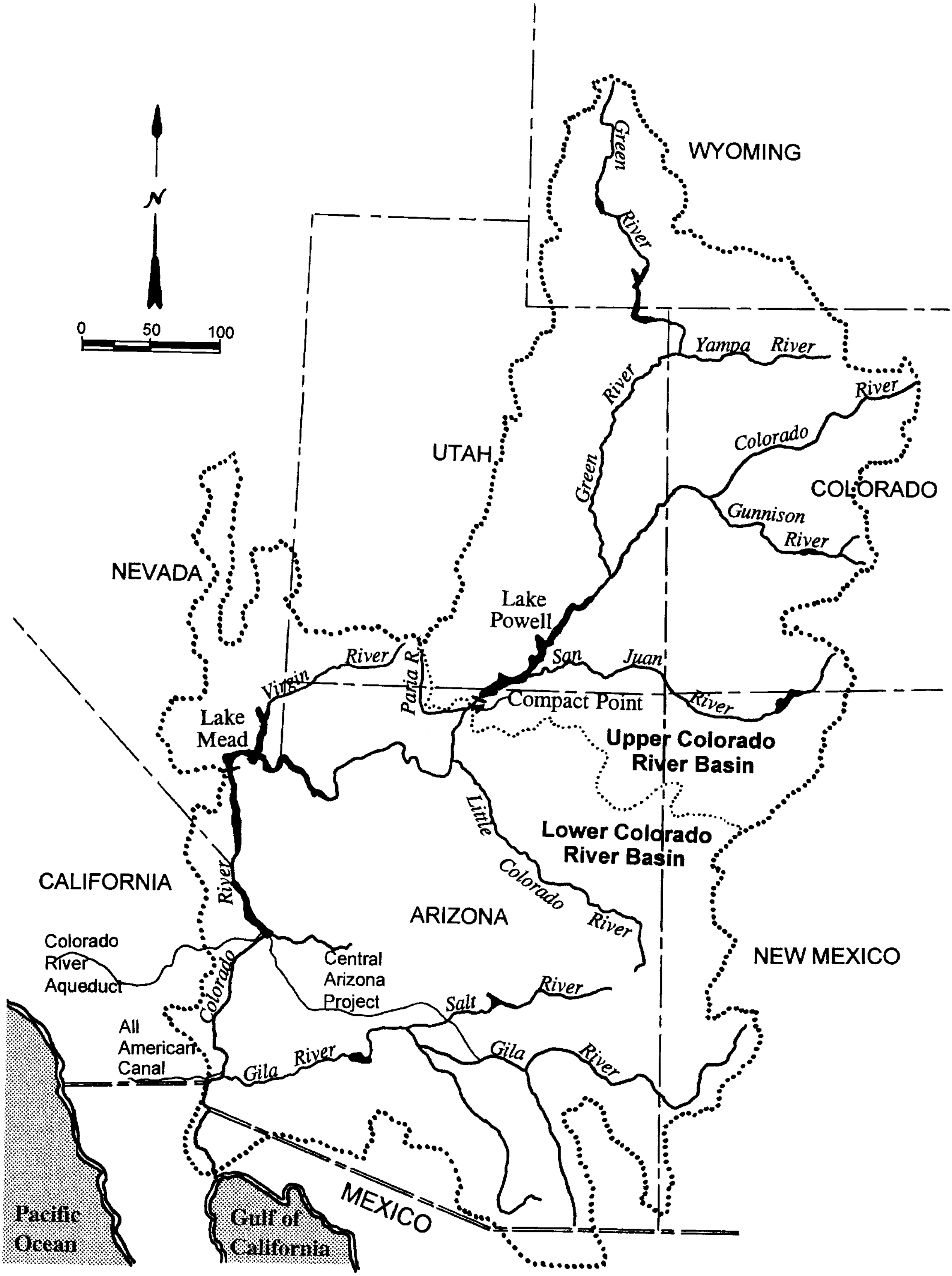

Figure 1. Colorado River Basin.

Ferry, just downstream of the point where the river crosses the Arizona-Utah border. The Upper Basin includes lands in the states of Colorado, New Mexico, Utah, Wyoming, and a small part of Northern Arizona, and is the principal source of inflow into the Colorado River system. The Lower Basin includes lands in the states of Arizona, California, Nevada, and New Mexico.

The natural flows in the basin are highly irregular in occurrence. While the annual natural flow at Lees Ferry, Arizona (the location of a streamflow gaging station, about 1 mile upstream of the Colorado River Compact point at Lee Ferry, Arizona), has averaged 15.2 million acre-feet (maf) over its period of record, flows in excess of 23 maf and less than 7 maf have been recorded. Over 70 percent of the annual natural flow occurs in the months of May, June, and July. Flows have been recorded for less than 100 years at most gaging points on the river.

Many reservoirs alter the natural flow of the Colorado River. The 14 reservoirs modeled in the Colorado River Model contain a total active capacity of 61,375,000 acre-feet. The two principal reservoirs, Lakes Powell and Mead (formed by Glen Canyon and Hoover Dams, respectively), provide over 50 maf of storage. Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin. The Lower Basin diversions tend to be larger and considerably fewer in number.

The Colorado River is already one of the most fully developed in the world. However, additional storage and diversion projects are being planned and actively pursued throughout the basin. Current water development plans of the individual states generally anticipate full development of their legal entitlements by the year 2060.

INSTITUTIONAL SETTING

The allocation of water within the Colorado River Basin is constrained within an institutional setting which has evolved from judicial, statutory, and administrative decisions collectively known as the Law of the River. These include the Colorado River Compact (1922), the Boulder Canyon Project Act (1929), the California Seven Party Agreement (1931), the Mexican Water Treaty (1944), the Upper Colorado River Basin Compact (1948), the Colorado River Storage Project Act (1956), the Supreme Court Decree in Arizona v. California (1963), the U.S. Army Corps of Engineers' Water Control Manual for Flood Control, water delivery contracts, and the Criteria for Coordinated Long-Range operation of Colorado River Reservoirs (Operating Criteria), among others. Summaries of the relevant governing law can be found in Meyers (1966) and Nathanson (1978).

THE COLORADO RIVER MODEL

The Colorado River Model simulates the Colorado River system by using a network flow algorithm (Texas Water Development Board, 1972; Clasen, 1968; Barr *et al.*, 1974) to perform, at each time-step, a static optimization of water allocation within a given system of priorities in a river basin network. Various institutional and physical settings are represented by arc connections, constraints, and costs and so may be evaluated by adjusting those parameters. Because water allocation in the basin is driven primarily by institutional rather than economic principles, the optimization capability of the network algorithm is used for efficient simulation and priority-based allocation.

The model has the same temporal and spatial resolution as the U.S. Bureau of Reclamation's (USBR) model of the Colorado River, CRSS (Schuster, 1987; 1988a; 1988b), with certain enhancements. Thus, the model uses a monthly time-step and includes 107 river reaches, 14 basin reservoirs, 29 inflow points, and 265 individual consumptive use points. An earlier generation of the Colorado River Model was used by Brown *et al.* (1988; 1990) in a study of the disposition of streamflow increases from the Arapaho National Forest.

System processes simulated in the model include most processes generic to any large river basin, such as water allocation, reservoir operations, evaporation, hydropower generation, and salinity. The model also simulates operations specific to the Colorado River Basin and the Law of the River including flood control releases, an objective minimum release from Lake Powell of 8.23 maf per year, inflow forecasting, calculation of the Section 602(a) storage criterion, equalization between Lakes Powell and Mead, the Colorado River Compact requirement of a 75 maf, 10-year moving total minimum delivery at Lee Ferry, and the declaration and quantification of shortages and surpluses in the Colorado River Basin (Hydrosphere's Colorado River Model Technical Overview, 1994).

SYSTEM SIMULATIONS

Two simulations of the Colorado River were made: one assuming the occurrence of a 38-year severe sustained drought cycle and a second assuming a 38-year period of inflows representative of historical conditions. The two simulations used the same assumptions regarding operational protocols, demands for consumptive use of water, and initial conditions.

Initial Conditions

System starting conditions are set by initializing reservoir starting contents and salinity levels. Starting contents were set to reported storage on October 1, 1991. Capacities and starting contents for the system reservoirs are shown in Table 1.

TABLE 1. Reservoir Initial Conditions (thousands of acre feet).

Reservoir	Active Capacity	Starting Contents
Fontenelle	345	267
Flaming Gorge	3,724	3,194
Starvation	255	255
Taylor Park	106	89
Blue Mesa	830	669
Morrow Point	117	117
Crystal	18	17
Navajo	1,642	1,635
Powell	24,454	14,654
Mead	27,019	19,200
Mojave	1,810	1,371
Havasu	619	557
McPhee	381	381
Ridgway	55	55

Inflow Hydrology

Two inflow sets were used for this study, a historical set and a severe sustained drought set. An inflow set consists of monthly time-series inflow data for 29 locations throughout the Colorado River Basin. The monthly values represent headwater flows on the mainstem and on major tributaries like the Green, Gunnison, San Juan, and Duchesne Rivers as well as gains along major tributaries or along the mainstem. For the most part, the inflow data are natural flows; that is, they represent unregulated, unimpaired streamflows. Some of the inflow data are gaged flows and hence reflect upstream regulation. The results of the model runs are expressed as simulated flows and also reflect upstream operations, including diversions, storage, and releases from storage. The two inflow hydrology sets used for this study, the historical streamflow set and the severe drought set, are described below.

Historical Streamflow Hydrology. The inflows used to represent the "normal" hydrology are for the 38-year period from October of 1938 through September of 1975. This period was selected because the average annual flow at Lees Ferry from 1938 through 1975 is equal to the median value of the average flows at Lees Ferry (14.1 maf) over the 41 38-year periods in the period of record (1906-1983). The larger set of historical inflows, from 1906-1983, were developed by the USBR for input to the CRSS model. Most of the Upper Basin inflows in the historical data set are natural flows. The Lower Basin inflows which represent tributaries, like the Bill Williams, are actual gaged flows or estimates of gaged flows. The Lower Basin inflows that represent gains are natural flows calculated by backing out upstream operations.

Severe Sustained Drought Hydrology. Derivation of the severe and sustained drought inflow set is described in Tarboton (1995). The period selected for analysis was 1579 to 1600. This 22-year period was found to contain the most severe drought in over 500 consecutive years of reconstructed streamflows. The annual flows in this period were rearranged to produce a drought of exceptional severity and were appended with originally-ordered reconstructed streamflows (1601-1616), to create a 38-year inflow data set which contained both the drought and a recovery period. This inflow configuration was adopted to represent a severe sustained drought in this and other project analyses.

The mean of the 38-year severe drought streamflow at Lees Ferry is 12.68 maf, and the mean of the 38-year historical trace is 14.1 maf. The drought streamflow trace begins with a total annual flow at Lees Ferry of 12.74 maf in the first year, jumps to 17.23 maf in the second year, and thereafter declines until it drops to its lowest level of 4.57 maf in year 21. The system starts to recover from the drought condition in year 22. The average streamflow of the severe drought trace over the first 21 years of the study period is 11.09 maf. A hydrograph and other characteristics of the severe drought are presented by Tarboton (1995).

Depletions

Water demands in the Colorado River Model are simulated as "depletions," the amount of water delivered for use minus the amount of water that returns to the river after use. Total depletions increase over the 38-year period of the simulations, beginning with estimates of actual water use for 1992 and progressing to projected values for subsequent years. Three levels of projected future depletions – referred to as low, medium, and high – were developed for use in the Severe Sustained Drought Project (Booker, 1995). The medium level was used for the study reported in this paper. The depletion estimates were, for the most part, derived from data developed by the USBR for its 1991 Annual Operating Plan, dated July 22, 1991. This depletion level assumes demand growth is represented by the USBR schedule for years 1992 to 2030, but with agricultural uses fixed at 1992 levels. The Las Vegas, Nevada, depletion is assumed to grow with projected population increases. The Central Arizona Project (CAP) depletion fluctuates over the study period, according to a schedule developed in the gaming exercises described by Henderson and Lord (1995).

The USBR depletion estimates on which the depletion data for this analysis are based were developed through model studies that included consideration of water supply, legal entitlement, current and expected delivery capacity, and expected development of water-using projects. Thus, they cannot be considered econometric estimates of demand for water.

RESULTS

Depletions

The simulations show that a severe sustained drought would heavily affect the Upper Basin states (Colorado, Nevada, New Mexico and Utah) but would have little impact on water use in the Lower Basin states (Arizona, California, and Nevada) for the projected depletion levels assumed. Results indicate that the Upper Basin states would experience a depletion shortfall of almost 59 percent in the worst drought year of the severe drought scenario. In contrast, the Lower Basin states would experience a depletion shortfall of about 3 percent of their basic entitlements in the worst drought year. Under a severe drought, all of the Lower Basin shortages would occur in Arizona and Nevada. California depletions would not be reduced below their basic entitlements; however, the Metropolitan Water District of Southern California (MWD), which serves the Los Angeles metropolitan area, would be deprived of surplus deliveries which would be available to it under historical streamflows. Water deliveries to Mexico would not be reduced below the 1.5 maf per year entitlement under a severe drought, though surplus deliveries to Mexico would be less than under historical streamflows. Deliveries to consumptive uses in the Upper and Lower Basins, under the severe drought and historical streamflow scenarios, are summarized in Table 2.

The minimum depletions for the Lower Basin states are the same under the severe drought scenario as under the historical scenario because the minimum demand for water, at the start of the study period, was lower than even the shorted deliveries later in the simulations. Upper Basin depletion shortfalls occurred in eight years of the 38-year study period in the drought scenario. Approximately 2.0 maf of Upper Basin depletions are present perfected rights; that is, their water rights were perfected prior to June 15, 1929, the date of enactment of the Boulder Canyon Project Act and therefore are not subject to calls for water under the Colorado River Compact. Under the severe drought scenario, even the present perfected rights suffered shortfalls in the two worst drought years because of local water supply deficits. In contrast, there were only two years in which depletion shortfalls to the Lower Basin occurred under the

TABLE 2. Annual Depletions in the Colorado River Basin (thousands of acre feet).

Region	Severe Drought			Historical Streamflows		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Upper Basin	1,809	4,632	3,999	3,887	4,632	4,304
Lower Basin						
Arizona	1,782	2,566	1,894	1,782	2,776	2,004
California	4,389	4,984	4,419	4,389	5,101	4,485
Nevada	201	264	243	201	264	243
Total Lower Basin	6,372	7,814	6,556	6,372	8,141	6,732
Mexico	1,516	1,516	1,516	1,516	3,202	1,671

drought scenario, years 22 and 23, when the active contents of Lake Mead dropped below the shortage level of 10.762 maf, prompting a shortage declaration. When a shortage is declared, deliveries to CAP are curtailed to the minimum annual delivery of 450,000 acre feet, and a shortage equal to 4 percent of the CAP curtailment is imposed on Nevada. California's normal entitlement depletions were not affected in any year during the study period, though surplus deliveries to California were 69 percent less, on average, under the drought than under the historical streamflows. Surplus declarations were made twice, in years 6 and 7, of the drought scenario and were taken by California and Arizona. In the historical scenario, surplus declarations were made in eight of the 38 years.

Streamflows

The simulations showed that a severe sustained drought would lead to an average monthly streamflow reduction of up to 12 percent at some locations, when compared to historical streamflow conditions. Table 3 below contains a summary of the streamflows at nine locations in the basin for the two scenarios.

With the exception of streamflows at the San Juan River confluence, the average monthly streamflows were lower under the drought scenario than under the historical scenario for all of the streamflow locations listed. The reduction in average streamflows ranges from 6 to 12 percent. The minimum flow for some stream reaches is zero because no minimum streamflow requirements were assumed for these simulations; therefore, in some months, the entire flow went to storage or was depleted to meet consumptive use requests.

The natural and simulated annual flows at Lee Ferry under the two scenarios are shown in Figure 2. Except for minor inflows from the Paria River, the simulated streamflows at Lee Ferry reflect releases from Lake Powell. In the historical streamflow scenario, the annual simulated flow at Lee Ferry did not drop below the 8.23 maf objective release throughout the 38-year study period and actually exceeded 9.0 maf in 11 years of the 38-year study period. Releases above the 8.23 maf objective were made to equalize the contents of Lakes Powell and Mead as provided for in the Operating Criteria. There were also six years in which at least some water spilled from Lake Powell.

In contrast, the total annual flow at Lee Ferry for the severe drought scenario dropped below the annual objective release level in 4 years of the 38-year study period. The total annual flow at Lee Ferry was 4.61, 4.55, 2.97, and 5.08 maf in years 19, 20, 21, and 22, respectively, as the drought intensified. A Colorado River Compact call occurred in year 21 when the 10-year moving total at Lee Ferry dropped below 75 maf. However, a release required to bring the 10-year total up to the 75 maf level could not be made in year 21 because inflows and reservoir storage in the Upper Basin were not enough to satisfy both the Compact call and the present perfected rights. Only 2.97 maf could be delivered in year 21 from the Upper Basin, and those flows occurred only in months in which Upper Basin inflows exceeded the consumptive use requests of the present perfected rights. The 75 maf moving total delivery requirement was not met again until year 26, four years after the system had started to recover from the severe drought.

TABLE 3. Monthly Streamflow at Selected Points in the Colorado River Basin (thousands of acre feet).

Region	Severe Drought			Historical Streamflows		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Green River Below Fontenelle	8	626	94	8	640	100
Green River Below Flaming Gorge	0	810	104	0	761	108
Yampa River Above Green Confluence	0	773	104	0	812	116
White River Above Green Confluence	0	193	36	0	209	38
Gunnison River Below Curecanti	2	719	128	15	746	143
San Juan River Above Colorado Confluence	0	822	101	0	1,207	96
Colorado River Above Powell	20	3,944	704	82	4,225	764
Colorado River at Lees Ferry	2	2,043	687	309	2,321	741
Colorado River Below Mead	245	1,006	661	296	1,666	702

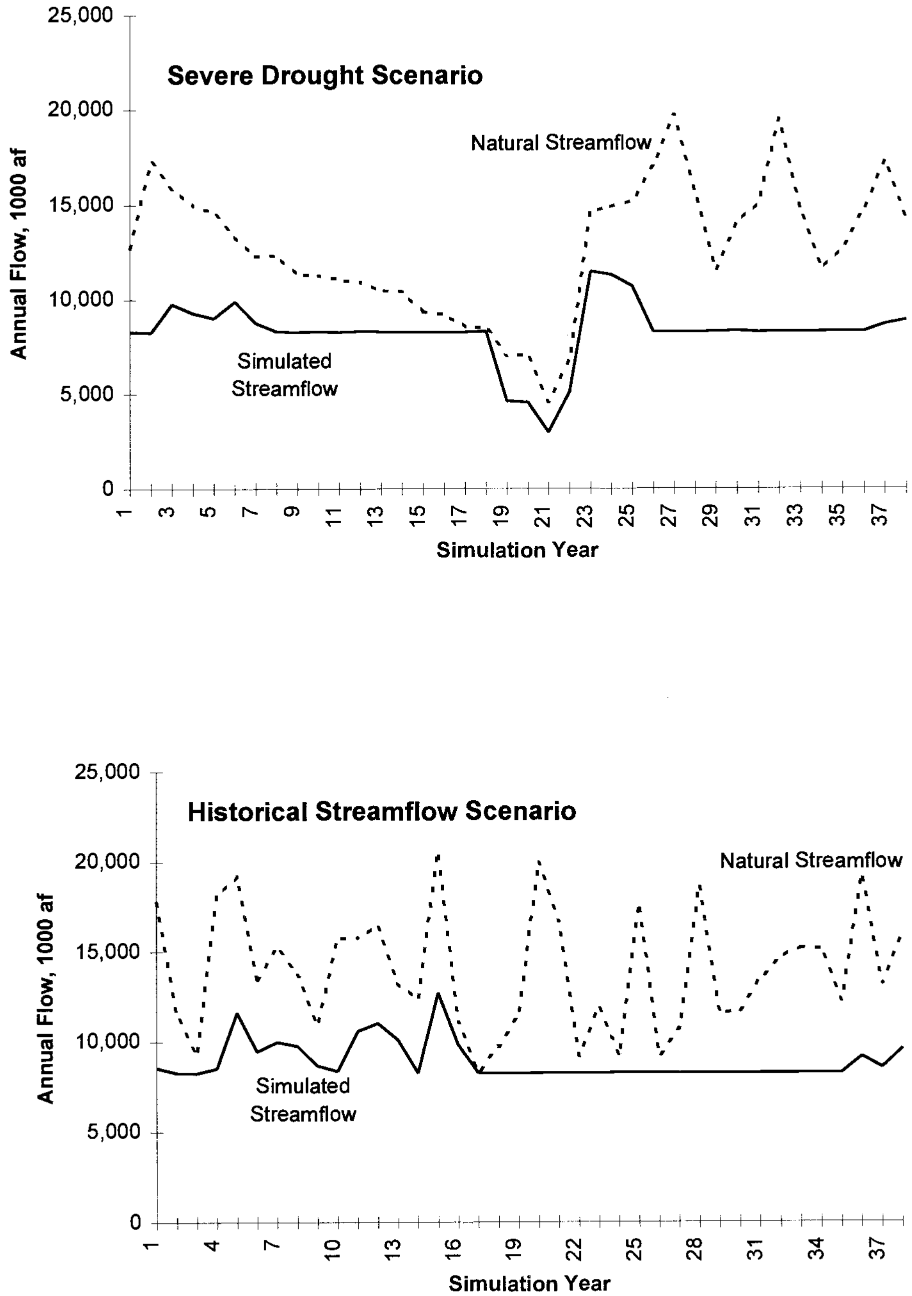

Figure 2. Annual Natural and Simulated Flows at Lee Ferry, Arizona.

Reservoir Contents

Storage in Upper Basin reservoirs, including Lake Powell, would decline to dead storage levels during the worst years of a severe sustained drought. This is in sharp contrast to reservoir contents in the Lower Basin, which would still have water in active storage during the worst drought years (Figure 3). The marked difference between storage in the Upper and Lower Basin reservoirs is a result of water being released from the Upper Basin to meet the objective release requirement, to be stored in Lower Basin reservoirs.

In the severe drought scenario, Lake Powell contents were drawn down to dead storage by the end of year 18. Active storage in Lake Powell was zero for eight years until the end of year 25. The active contents of Flaming Gorge Reservoir tracked those of Lake Powell; that is, the reservoir contents declined to the dead storage level and remained there for

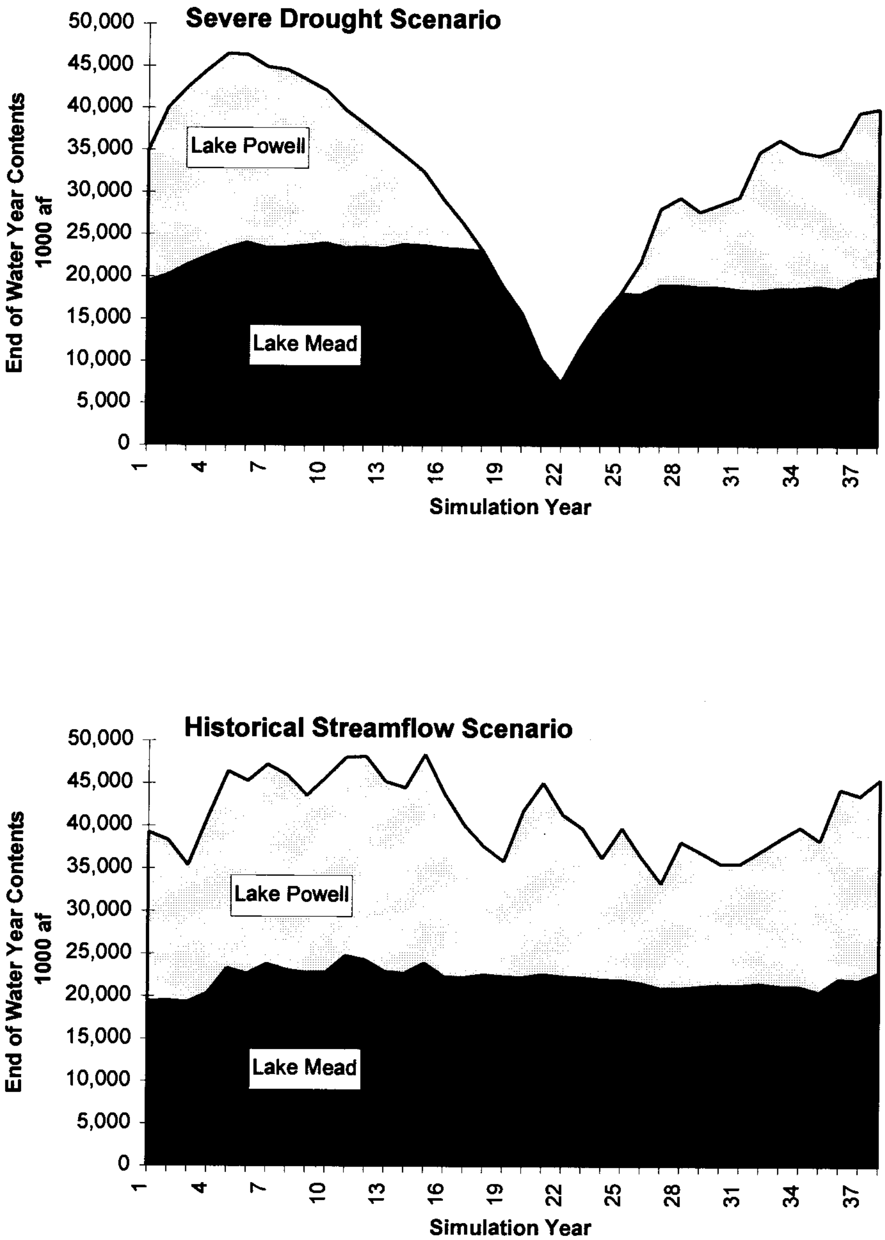

Figure 3. Simulated Lake Powell and Lake Mead Contents.

several years. In contrast, throughout the historical streamflow scenario, the contents of Lake Powell and Flaming Gorge Reservoir were never drawn down to dead storage. The minimum active storage contents of Lake Powell and Flaming Gorge Reservoir under the historical streamflow scenario were 13.08 and 2.20 maf, respectively.

Lake Mead was not as severely affected as the Upper Basin reservoirs. Under the severe drought scenario the lowest active storage volume observed in Lake Mead was 7.50 maf, in year 22. The relatively high reservoir volumes maintained in Lake Mead occurred because of several reasons:

(a) the Operating Criteria require equalization releases from Lake Powell to Lake Mead as long as the forecasted end-of-water-year contents in Lake Powell exceeded those of Lake Mead (subject to other limitations);

(b) the Operating Criteria also require an annual minimum objective release of 8.23 maf from Lake Powell to Lake Mead; and

(c) the Colorado River Compact requires a 75 maf, 10-year moving total delivery at Lee Ferry.

Salinity

The severe drought would result in increased salinity in the system. The salinity impact would be less severe in the Upper Basin because salinity levels increase from upstream to downstream, so that the greatest effect would be felt by the downstream-most users. Salinity was somewhat mitigated by the shortfalls in Upper Basin, which reduced return flows and thus the salt load, during the worst years of the drought. Salinity below Hoover Dam for the two simulations are summarized in Table 4.

By most measures, the salinity in the river is higher under the severe drought than under the historical streamflows scenario. The one exception is frequency of exceedence of the salinity criterion below Hoover Dam of 723 parts per million (ppm). The criterion was exceeded in 32 of the 38 years in the historical streamflow scenario and was exceeded in 30 of the 38 years in the severe drought scenario. This effect is to some degree a result of the simulation of only active storage rather than total storage in the Colorado River Model; when Lake Powell empties, its salt inventory is eliminated so that, in subsequent months, the reservoir concentration assumes the inflow concentration. In reality, inflows in subsequent months would mix, to some extent, with the highly concentrated water in dead storage, thus extending the period over which salinity levels are elevated.

Hydropower

Colorado River hydropower generation would be considerably lower under a severe drought than under historical streamflows (Table 5). The simulations show that the total annual energy generated in the system would be 84 percent lower in the worst drought year of the severe drought scenario, compared to the minimum generated in the historical streamflow scenario when the contents of Lake Mead fall below the minimum power pool level.

In the severe drought scenario, an abrupt decrease in the generated energy occurred when the level of Lake Powell dropped below the minimum power pool, in year 17 of the drought. Thereafter, the power plant at Glen Canyon Dam (Lake Powell) did not contribute to the total system energy until five years after the drought ended, when the level of Lake Powell rose above the minimum power pool. A second abrupt decrease in the total system energy generation occurred when the level of Lake Mead dropped below the minimum power pool, in year 22 of the severe drought. In that year, the lowest energy generation year in the study period, 73 percent of the total energy generated in the Colorado River system was from the powerplants at Lake Havasu and Lake Mojave.

DISCUSSION

The simulations show that the Colorado River system would be remarkably resilient in the face of an exceptionally extreme, even unrealistic drought of the sort postulated in this study. However, the impacts of the drought would fall disproportionately on the states of the Upper Basin. Our studies indicate that, under the current institutional setting, over half of the Upper Basin consumptive use requests would be unmet in the worst drought year, the same year in

TABLE 4. Colorado River Salinity Below Hoover Dam (parts per million).

	Average	Maximum	Minimum
Historical Streamflows Scenario	859	1,083	602
Severe Drought Scenario	908	1,530	648

TABLE 5. Colorado River Energy Generation (including 11 power plants) (annual gigawatt-hours).

	Average	Maximum	Minimum
Historical Streamflows Scenario	9,716	12,673	8,778
Severe Drought Scenario	7,704	10,625	1,439

which Lake Mead held almost 7.5 maf of water in storage. In contrast, the worst Lower Basin shortfall would only be about 3 percent and would occur in Arizona and Nevada. Though California's basic entitlement would be immune to the drought, California's demand for Colorado River water exceeds its normal entitlement. For example, though MWD's Colorado River entitlement is 487,000 af, the Colorado River Aqueduct can deliver 1.2 maf per year and has frequently done so. The frequency of surplus deliveries to MWD would be seriously curtailed under a severe drought. At the same time, deliveries to California agriculture would not be curtailed from their 3.85 maf entitlement.

The disproportionate distribution of impacts in a severe sustained drought suggests the need for institutional coping mechanisms. Several such mechanisms are identified in Henderson and Lord (1995) and evaluated in Sangoyomi and Harding (1995).

ACKNOWLEDGMENTS

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WATER RESOURCES BULLETIN
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THE LAW OF THE COLORADO RIVER: COPING WITH SEVERE SUSTAINED DROUGHT[1]

Lawrence J. MacDonnell, David H. Getches, and William C. Hugenberg, Jr.[2]

ABSTRACT: The waters of the Colorado River are divided among seven states according to a complex "Law of the River" drawn from interstate compacts, international treaties, statutes, and regulations. The Law of the River creates certain priorities among the states and the Republic of Mexico, and in the event of a severe sustained drought, the Law of the River dictates the distribution of water and operation of the elaborate reservoir system. Earlier work indicated that there is remarkable resilience in the system for established uses of water in the Lower Basin of the Colorado River. This work shows, based on an application of the Law of the River using computer modeling of operations of facilities on the Colorado River, that there may be serious environmental consequences and related legal restraints on how the water is used in times of shortage and that the existing legal and institutional framework governing the Colorado River does not adequately address all the issues that would be raised in a severe sustained drought. Several possible legal options for dealing with drought in the context of the Law of the River are identified.
(KEY TERMS: social and political; water law; water policy/regulation/decisionmaking; water resources planning; watershed management.)

INTRODUCTION

In November 1922, representatives of the seven Colorado River Basin states met, under the chairmanship of Secretary of Commerce Herbert Hoover, at Bishop's Lodge near Santa Fe, New Mexico, to "divide the waters" of the Colorado River in a manner intended to avert almost certain legal warfare (Hundley, 1975). Foremost on the mind of W. F. McClure, the representative from California, was attaining a clear (and substantial) entitlement of Colorado River water for his state, thereby opening the way for congressional authorization of the funds needed to build what became Hoover Dam and the All American Canal. Similarly, Delph Carpenter, the Colorado representative and arguably the most influential of all the state representatives, was committed to ensuring the opportunity of his state (and others such as New Mexico, Utah, and Wyoming that were growing more slowly than California) to develop and use Colorado River water in the future. Unfortunately, the negotiators believed they were dividing an annual average flow of 16.4 million acre-feet (measured at Lee Ferry). However, based on subsequent long-term tree-ring analysis, the actual annual average flow of the Colorado River appears to be more like 13.5 million acre-feet (Stockton and Jacoby, 1976; Kneese and Bonem, 1986).

When the parties were unable to agree on specific allocations for each of the participating states, Hoover saved the negotiations from failure by proposing to divide the available water between an "Upper" and a "Lower" Basin with the geographic division at Lee Ferry in northern Arizona. This agreement – which was eventually adopted by Congress as the Colorado River Compact ("Compact") – allocates 15 million acre-feet ("maf") of annual "exclusive beneficial consumptive use," 7.5 maf each to the Upper and Lower Basins, with an additional 1 maf to the Lower Basin. The Compact also anticipated additional water being committed to Mexico and a future allocation to the two Basins of "surplus" water. Given the misapprehension concerning the amount of water actually available, the operative provision of the Compact is Article III(d), which commits the Upper Basin to deliver at Lee Ferry 75 maf during every consecutive ten-year period (i.e., a moving ten-year average of 7.5 maf per year).

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Perhaps most fundamentally, the Compact was intended to provide a sense of certainty to the parties. Lower Basin states and Upper Basin states each believed they were obtaining rights to use consumptively at least their respective expressed apportionment of Colorado River water. The Lower Basin states (certainly California) expected to develop and use more than this minimum amount. Since none of the parties expressed any real concern with the possibility of long-term drought, the Compact makes no provision for dealing with shortages of water.

This article addresses the ways in which the interstate compacts, international treaties, statutes, and regulations, known collectively as "The Law of the River," affect allocation decisions likely to be confronted in the event of a long-term, severe drought. The analysis is organized in a manner familiar to those conversant with the prior appropriation doctrine: according to legal priority. While the Law of the River is not technically a priority system, as a practical matter it does operate to create either express or implied priorities among those with legally recognized allocations of water. It establishes priorities between the United States and Mexico, between rights which pre- and post-date the Colorado River Compact, between the Upper and Lower Basins, and among uses of compact-allocated water within both the Lower and Upper Basins. These priorities are discussed in this article as are their implications for water allocation in the event of a prolonged and severe drought within the Colorado River Basin. Finally, the implications of water quality and endangered species protection are considered, since, under certain circumstances, legal requirements associated with these concerns are capable of trumping other water use priorities.

At the outset, it is important to acknowledge the extraordinary efforts already made to "drought-proof" users of Colorado River water, particularly those in the Lower Basin. Water storage facilities with a capacity roughly four times the average annual flow of the river have been constructed, almost all by the Bureau of Reclamation (see Map of the Colorado River Basin, Figure 1). Under ordinary circumstances, such massive storage should render issues of priority largely moot. However, under the extreme scenarios of prolonged drought investigated in this project, allocative priorities become significant. During periods of severe, sustained drought in the Colorado River Basin, water use decisions would presumably be made on the basis of the priorities derived from the Law of the River. This article seeks to explicate priorities, to identify areas of uncertainty, and to suggest the need for added flexibility in the existing allocation system to improve its ability to satisfy demands on the Colorado River in times of prolonged drought.

WATER FOR MEXICO

Under our interpretation of the Law of the River, the treaty-based delivery obligation to Mexico is the senior priority on the Colorado River. The 1944 "Treaty with Mexico Respecting Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande" guaranteed 1.5 maf per year of Colorado River water to Mexico. Efforts to clarify Mexico's claim to the Colorado River had been underway for many years (Hundley, 1966). Article III(c) of the 1922 Compact recognized the likelihood of such an agreement and provided that water for Mexico should be supplied from the unallocated "surplus" thought to be available, with any "deficiency" to be borne equally by the Upper Basin and the Lower Basin. Since there is, on average, no long-term unallocated surplus water in the river, the effect of this provision is to obligate both the Upper and Lower Basins each to ensure the annual availability to Mexico of 750,000 acre-feet of Colorado River water.

As a treaty commitment anticipated and agreed to in a congressionally approved interstate compact, the delivery obligation to Mexico is legally binding even during severe, sustained drought. Indeed, the priority of the delivery obligation to Mexico is reflected in the operation of the Glen Canyon Dam. The Colorado River Basin Project Act of 1968 directed the Secretary of the Interior to develop long-term operating criteria for operation of Glen Canyon and other Upper Basin dams authorized by the Colorado River Storage Project Act of 1956. Highest on the list of priorities to be satisfied under the operating criteria was the Upper Basin's delivery obligation under the treaty. Moreover, unlike much of the Law of the River, the 1944 Treaty with Mexico explicitly addresses the possibility of a severe drought. Thus, Article 10 states:

> In the event of extraordinary drought or serious accident to the irrigation system in the United States, thereby making it difficult for the United States to deliver the guaranteed quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) a year, the water allocated to Mexico under subparagraph (a) of this Article will be reduced in the same proportion as consumptive uses in the United States are reduced.

In other words, an "extraordinary drought" must make it "difficult" to meet the treaty obligation. Just how this determination is to be made remains

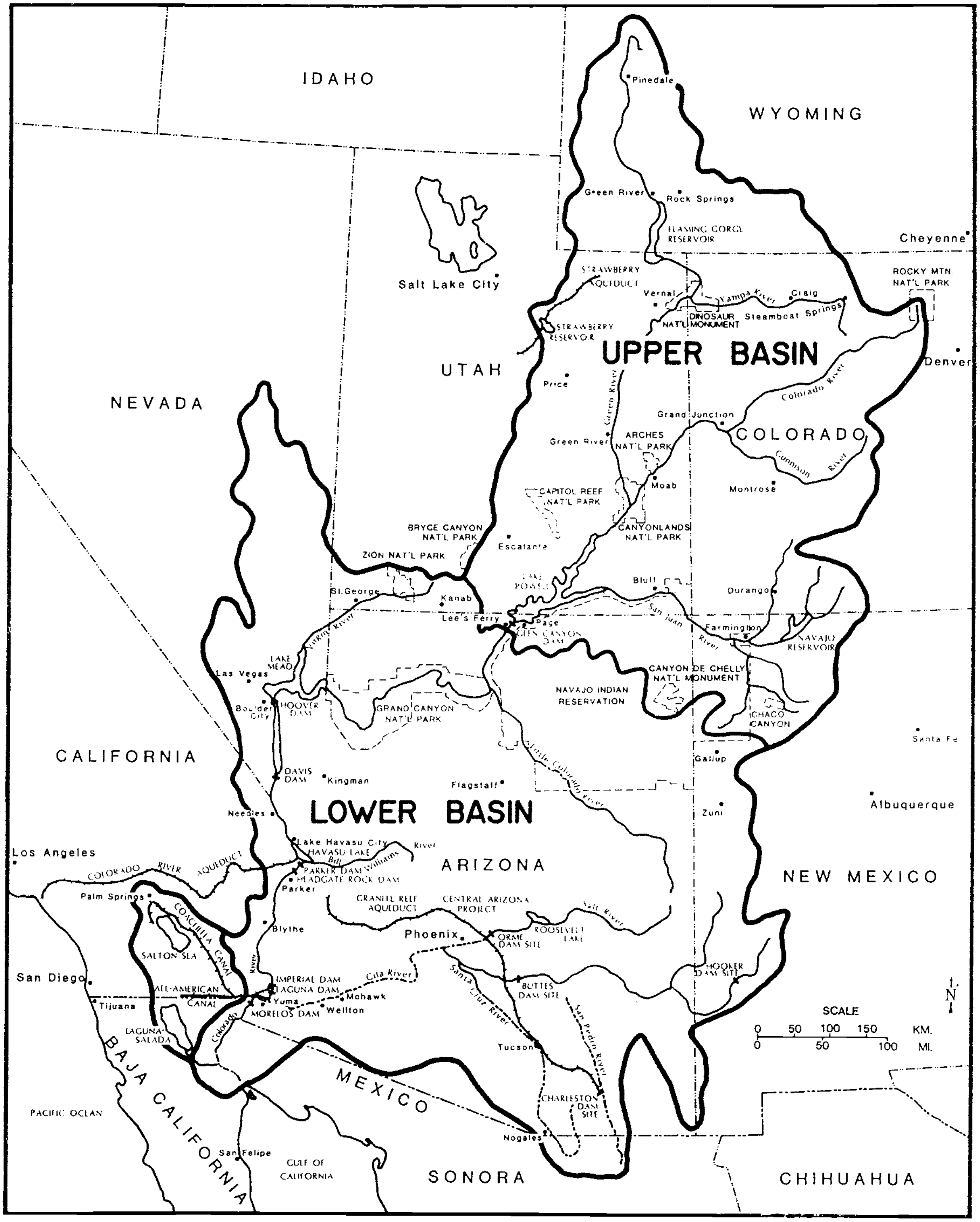

Figure 1. Map of Colorado River Basin.
(Source: Gary D. Weatherford and F. Lee Brown, New Courses for the Colorado River, pg. xx, 1986.)

unclear; however, under some circumstances, the delivery obligation can be reduced. The formula is based on a reduction in consumptive uses in the United States. Presumably, this means that the Upper and Lower Basins can reduce their deliveries to Mexico by the percentage that the drought-caused reductions in their consumptive uses of Colorado River water represent to their average historical consumptive uses of this source of supply, although this is far from clear. Indeed, the meaning of "consumptive" uses – a term used in the 1922 Compact – is also unclear (Getches, 1985, pp. 423-424).

PRESENT PERFECTED RIGHTS

Next in seniority are tribal reserved water rights and other "present perfected rights" that pre-date the Colorado River Compact. Article VIII of the Colorado River Compact states that "[p]resent perfected rights to the beneficial use of water of the Colorado River System are unimpaired by this compact." At the time the Compact was being negotiated, the Reclamation Service estimated that nearly 2.5 million acres of land were being irrigated in the United States with Colorado River water (Hundley, 1975, at 146-47). Present perfected rights are not further defined, but they presumably encompassed all consumptive uses already in being in 1922.

Among these "present perfected rights" were those controlled by irrigators in the Imperial Valley of California, who had been periodically devastated by floods and were largely dependent on diversions from the Colorado River in Mexico. The 1928 Boulder Canyon Project Act satisfied the desires of this very active contingent of Californians by authorizing the construction of Hoover Dam for river regulation and flood control and by providing needed federal financial and technical support to build a new canal that would deliver Colorado River water to the Imperial Valley through lands entirely within the U.S. (thus, the "All American Canal"). The 1928 Act also responded to the urgency of Los Angeles interests who wanted a reliable supply of hydroelectric power and a future water source. Because of the potentially heavy demands that these proposed uses would put on the river, the Boulder Canyon Project Act also expressly recognized "satisfaction of present perfected rights" as a purpose of the dam.

Further, Article VIII of the Compact provides:

> Whenever storage capacity of 5,000,000 acre-feet shall have been provided on the main Colorado River within or for the benefit of the Lower Basin, then claims of such [present perfected] rights, if any, by appropriators or users of water in the Lower Basin against appropriators or users of water in the Upper Basin shall attach to and be satisfied from water that may be stored not in conflict with Article III.

Under normal operation of the prior appropriation doctrine, a senior downstream appropriator can protect a right to water by placing a "call" on the stream, thereby preventing a junior upstream user from exercising a competing right to water. However, construction of Hoover Dam, by interposing a reservoir – Lake Mead – to buffer demands of the two Basins, obviated the possibility that Lower Basin present perfected rights would seek to impose a call on Upper Basin present perfected rights.

Nevertheless, it remained for litigation in the U.S. Supreme Court many years later to produce a definition of present perfected rights. In the 1964 Decree implementing its decision in *Arizona v. California,* the Court defined a perfected right as

> a water right acquired in accordance with State law, which right has been exercised by the actual diversion of a specific quantity of water that has been applied to a defined area of land or to definite municipal or industrial works, and in addition shall include water rights created by the reservation of mainstream water for the use of Federal establishments under Federal law whether or not the water has been applied to beneficial use; . . . (376 U.S. 340, 341, 1964).

The Court included as perfected rights in the Lower Basin those established as of the effective date of the Boulder Canyon Project Act (June 25, 1929). The Court also recognized tribal reserved water rights under the so-called "Winters Doctrine" [from *United States v. Winters,* 207 U.S. 564 (1908)] as being present perfected rights. Moreover, the Court ruled that, in any year in which less than 7.5 maf of Colorado River water is available for consumptive use in the Lower Basin states (Arizona, California, and Nevada), the Secretary of the Interior is to administer the river so as to satisfy first all those holding present perfected rights and to do so on a chronological priority basis without regard for state lines.

In its 1964 Decree, the Supreme Court also recognized a process for identifying and quantifying present perfected rights to use Colorado River water in the Lower Basin. In a 1979 Supplemental Decree, the Court specified these rights in the three states by priority date and by annual quantity of water that may be diverted [(*Arizona v. California,* 439 U.S. 419 (1979)]. Present perfected rights total more than 4 maf, including nearly 3 maf in California. Tribal water rights which are also present perfected rights, total about 900,000 acre-feet, most of which are in Arizona. Since most Indian water rights have not yet been put to consumptive use by their tribal owners, increased utilization of those rights by the tribes could exacerbate the effects of severe, sustained drought on other lower-priority users.

WATER FOR THE LOWER BASIN

While the 1922 Compact segmented the Colorado River into two basins with the dividing point at Lee

Ferry in Arizona, just below the present site of Glen Canyon Dam, that division assigned a higher priority to the Lower than to the Upper Basin. Each Basin is apportioned the "exclusive beneficial consumptive use" of 7.5 maf of water per year (including present perfected rights), and the Lower Basin is "given the right" to use an additional 1 maf. The apportionment, however, operates as a delivery guarantee in favor of the Lower Basin rather than a division of available waters.

Article III(d) of the 1922 Compact prohibits the Upper Basin from depleting the Colorado River, measured at Lee Ferry, below an aggregate of 75 maf of water in any ten-year period. Moreover, under Article III(e) of the Compact, the Upper Basin cannot "withhold" water that "cannot reasonably be applied to domestic and agricultural uses." Since the Upper Basin still has not developed consumptive water uses approaching its 7.5 maf-per-year ceiling, the practical effect of these provisions is generally to assure that the Lower Basin will receive at least 7.5 maf per year on average and potentially more in many years. Thus, while the Compact purported to apportion the Colorado River equally between the two Basins, in fact it works primarily to generate deliveries of water to certain water users in Arizona, California and Nevada. Congress further ensured that the Upper Basin would be able to meet its delivery obligations to the Lower Basin by authorizing construction of Glen Canyon Dam (and three other large projects in the Upper Basin) in the Colorado River Storage Project Act of 1956.

The emphasis on providing a minimum delivery of 7.5 maf per year to the Lower Basin is also evident in the way in which the Secretary of the Interior, under general congressional direction, has decided to operate Hoover Dam and Glen Canyon Dam. Section 602(a) of the Colorado River Basin Project Act of 1968 directed the Secretary of the Interior to develop long-range operating criteria ("operating criteria") for these reservoirs. The Secretary's present operating criteria call for a "minimum objective release" of 8.23 maf per year from Lake Powell (calculated by annualizing the ten-year 75 maf obligation to 7.5 maf, adding the Upper Basin's one-half share of the 1.5 maf Mexico commitment, and subtracting 20,000 acre-feet as the estimated annual inflow from the Paria River which enters the Colorado River below Glen Canyon Dam but above Lee Ferry). More than this amount of water must be released whenever storage in Lake Powell exceeds a certain level, but a minimum release of 8.23 maf is required regardless of water conditions in the Upper Basin. The Secretary is to review the operating criteria at least every five years and is authorized to make changes at those times.

Elements of the Law of the River also make allocations within as well as to the Lower Basin and establish priorities among states, among some users, and among certain uses in the Lower Basin. Perhaps most important is the 1963 U.S. Supreme Court decision in *Arizona v. California,* which found that, as a result of the 1928 Boulder Canyon Project Act, California held an allocation of 4.4 maf, Arizona 2.8 maf, and Nevada 300,000 acre-feet. If less than 7.5 maf of water is available, the Secretary has discretion to apportion the shortages. Present perfected rights must be satisfied first.

In 1929 the California legislature affirmatively recognized that its apportionment was limited to 4.4 maf as required by the Boulder Canyon Project Act. Then major Southern California water users established priorities among themselves to certain quantities of Colorado River water under a 1931 Seven Party Agreement. The first three priorities (for 3.85 maf of water) went to agricultural water uses in the Palo Verde Valley, Yuma Project (Reservation Division), Imperial Valley, and Coachella Valley (representing over 2.8 maf of present perfected rights); fourth priority (for 662,000 acre-feet) went to Metropolitan Water District of Southern California (MWD). Rights to unused or "surplus" supplies (above 4.4 maf) go first to MWD (662,000 acre-feet, of which 112,000 was allocated to San Diego) and then to the four irrigation districts (300,000 acre-feet).

The Colorado River Basin Project Act specifically gave California a higher priority to receive its 4.4 maf of water than any diversions to provide water for the Central Arizona Project (CAP). Arizona agreed to subordinate its CAP diversion rights in return for California's support for the project, which was authorized in 1968. The operating criteria for Hoover Dam describe three general operating conditions: **normal,** in which annual releases provide 7.5 maf per year to meet Lower Basin uses; **surplus,** in which additional water will be released; and **shortage,** in which the Secretary has the discretion to release less than 7.5 maf. In a shortage situation, all present perfected rights must first be satisfied and then the remainder of California's 4.4 maf. Nevada's contract deliveries must be satisfied ahead of deliveries to the CAP. Thus, by virtue of the Lower Basin's higher priority and especially California's preferred position therein, the Law of the River effectively shifts the burden of the consequences of severe, sustained drought, to Arizona and ultimately to the Upper Basin.

WATER FOR THE UPPER BASIN

The 1922 Compact appeared to apportion the beneficial consumptive use of 7.5 maf per year of Colorado River water to the Upper Basin. In fact, the amount actually available for use depends on available supplies and quantities in storage. In 1948 the Upper Basin states worked out a compact allocating their respective shares of Colorado River water. The Upper Colorado River Basin Compact ("Upper Basin Compact") allocated 50,000 acre-feet of annual consumptive use from the Colorado and Little Colorado Rivers to Arizona and then apportioned use of the remaining waters among the states of Colorado (51.75 percent), New Mexico (11.25 percent), Utah (23 percent), and Wyoming (14 percent) (see Table 1 below). The effect of the allocation is shown in Table 1. As shown, present uses are well below the theoretical 7.5 maf apportionment and are well within the supply capacity of the Colorado River under the historical average flow conditions derived from tree-ring studies (13.5 maf). Assuming the storage buffer has been exhausted, shortages begin to arise in some states as annual flows decline below 14 maf.

In anticipation of possible shortages, the 1948 Compact established the Upper Colorado River Commission ("Commission") and empowered the Commission to order curtailments of consumptive uses in the Upper Basin as required to meet downstream delivery obligations. As discussed more fully in the next section, Article IV(b) provides that, in the event of curtailment, any state that has exceeded its water allocation in the immediately preceding ten years must deliver the entirety of its aggregate overage to Lee Ferry in the year of the call, or a sufficient portion thereof to enable the Upper Basin to meet its delivery obligations under Article III of the Colorado River Compact.

Under Article IV(c), once aggregate overdrafts have been supplied, any remaining required curtailments are to be allocated among the four states in the same proportion as the previous water year's actual consumptive use bears to total consumptive uses in the Upper Basin, without regard for consumptive uses under present perfected rights. In addition, Article VII(d)(1) authorizes the Commission to make and report findings to the President as to whether the shortage provision of Article 10 of the Treaty with Mexico should be invoked.

Enactment of the Upper Colorado River Basin Compact cleared the way for federal support of the construction of major storage projects in the Upper Basin. The Colorado River Storage Project Act of 1956 authorized four projects: Curecanti (now the Aspinall Unit) on the Gunnison River in Colorado, Navajo Dam on the San Juan River in New Mexico, Flaming Gorge Dam on the Green River in Utah, and Glen Canyon Dam on the Colorado in northern Arizona. Construction of these additional storage facilities thus reflects a recognition that the Upper Basin would bear the burden of risk associated with the initial miscalculation of the likely annual flows of the Colorado River.

LEGAL REQUIREMENTS AND OPPORTUNITIES IN RESPONDING TO A SEVERE SUSTAINED DROUGHT

The preceding sections describe the general priorities by which decisions to allocate Colorado River water would presumably be made in a period of prolonged drought. Within this priority structure, however, flexibility to cope with severe, sustained drought varies. Thus, for example, while the treaty obligation to Mexico holds the highest priority, it also

TABLE 1. Consumptive Uses Allowed by the Upper Basin Compact.

Recipient	Compact Percent (percent)	Assumed Flow Conditions* at 16 maf	at 14 maf	at 12 maf	at 10 maf	Actual Uses** (1981-1985 average)
Arizona		.05	.05	.05	.05	.04
Colorado	51.75	3.86	2.95	1.91	.88	1.99
New Mexico	11.25	.84	.64	.42	.19	.38
Utah	23.00	1.71	1.31	.85	.39	.66
Wyoming	14.00	1.04	.80	.52	.24	.33
Upper Basin Total	100.00	7.5	5.75	3.75	1.75	3.40

*Assumes that a minimum of 8.25 million acre-feet of water must go to the Lower Basin.
**Bureau of Reclamation, Colorado River System Consumptive Uses and Losses Report, 1981-1985 (June 1991).

incorporates a mechanism by which the actual annual delivery may be reduced. More specifically, while the CORN computer model used for analysis of Colorado River operations in this project assumes that deliveries to Mexico will not be reduced until there is no storage remaining in Lake Mead, in fact the Treaty suggests the possibility of reducing deliveries to Mexico if any consumptive uses of Colorado River water in the U.S. are reduced. It seems likely that this provision would be invoked before Lake Mead is drained, but it is far from clear what that point would be. In any event, relatively little water would be saved by the U.S. under this provision.

Similarly, while operation of the Colorado River is heavily weighted toward assuring deliveries to the Lower Basin, and particularly the 4.4 maf allocated to California and the water allocated to pre-1968 users in Arizona and Nevada, the Secretary of the Interior has some discretion in deciding how to allocate shortages among Lower Basin users. Section 301(b) of the Colorado River Basin Project Act directs the Secretary to satisfy present perfected rights first, other water contract holders in California (up to the 4.4 maf allocation) second, and other contract holders and federal reservations in Arizona and Nevada third. Deliveries to the Central Arizona Project are to be curtailed as necessary to meet these other Lower Basin uses.

At present the Secretary has no explicit guidance by which to declare a shortage situation in the Lower Basin (that is, when there is inadequate water to release 7.5 maf for consumptive uses). The Bureau of Reclamation's Colorado River model assumes a shortage exists when the elevation of Lake Mead reaches 1095 feet (12 feet above the nominal minimum power pool and approximately 40 percent of active storage capacity). At this point CAP deliveries are assumed to drop abruptly from roughly 1.3 maf to 800,000 acre-feet per year. Further reductions would be made as necessary to meet present perfected rights and other contract rights established on the basis of the 7.5 maf Lower Basin apportionment.

Section 602(a) of the 1968 Colorado River Basin Project Act prioritizes the operation of the Upper Basin reservoirs and particularly Lake Powell, first, to supply the Upper Basin's Mexico delivery obligation; second, to meet the Colorado River Compact's requirement that the Upper Basin not cause the ten-year flow at Lee Ferry to be less than 75 maf; and third, to make additional releases determined to be reasonably usable by the Lower Basin without impairment of existing consumptive uses in the Upper Basin. The 1968 Act appears to require releases from Lake Powell as necessary to equalize its storage with that of Lake Mead. As discussed above, the operating criteria for Glen Canyon Dam establish a "minimum objective release" of at least 8.23 maf per year. More water may be released when there is a "surplus" but no adjustments are made in low flow years to compensate for releases in excess of 8.23 maf in high flow years. Such operations may satisfy Section 602(a) of the 1968 Act but create an inflexibility not required by the 1922 Compact which only places a ten-year – not an annual – delivery obligation on the Upper Basin.

Neither the 1968 Act nor the operating criteria provide for management of the Upper Basin reservoirs in anticipation of or under actual conditions of prolonged drought. Rather, all attention is focused on assuring the availability of at least 7.5 maf annually of consumptive uses in the Lower Basin, and on the circumstances under which more water may be released to satisfy Lower Basin demands compatible with optimum generation of electric power. The emphasis on optimizing power generation has been moderated somewhat by the Grand Canyon Protection Act of 1992, which forces consideration of recreational as well as fish and wildlife concerns. Though not prescriptive beyond its terms, the 1992 Act could inform the exercise of Secretarial discretion throughout the Basin.

Unlike the Colorado River Compact and subsequent statutes relating to the Colorado River, the Upper Basin Compact addresses the potential condition of inadequate water to meet consumptive uses. Such attention is perhaps not surprising in view of the direct linkage in the Upper Basin Compact between possible curtailment of Upper Basin uses and meeting the downstream commitments established in the 1922 Colorado River Compact. However, some ambiguity remains in the meaning of the "principles" that are to guide the Upper Colorado River Commission in ordering curtailments. First recourse is to those states consumptively using more water than they were entitled to under the Upper Basin Compact during the immediately preceding ten-year period. Except for Arizona (which has a fixed allocation of 50,000 acre-feet per year), each of the Upper Basin states has an allocation to consume a specified percentage of what was assumed to be 7.5 maf per year (less the Upper Basin's share of the delivery request for Mexico and up to 50,000 acre-feet per year for Arizona). Curtailments are to be made on the basis of the percentage of the downstream delivery obligation created by a state's share of the total consumptive use of Colorado River water in the Upper Basin during the preceding year. Consumption related to water rights perfected in Upper Basin states prior to November 24, 1922, is to be excluded from this calculation.

In sum, the collective pieces of the Law of the River create a more or less well-defined set of requirements by which shortages of Colorado River water are to be allocated among the large number of consumptive users in the Basin. In fact, much less attention has been given to questions of allocating shortages than to allocating "surpluses." Emphasis has been placed on avoiding shortages through the construction of a massive water storage system and on operating it to assure delivery of at least the minimum contracted allotments within the Lower Basin.

An earlier study of severe sustained drought in the Colorado River Basin ("Phase I Report," Gregg and Getches, 1991) included an analysis of water allocation under existing legal and institutional arrangements. That study assumed levels of drought severity drawn from reconstructed flows based on tree-ring studies covering a 400-year period and accounted for water sources available to California and Arizona in addition to the Colorado River. It attempted to determine the performance of existing water delivery and distribution systems. The report concluded that under the existing legal and institutional regime, most of the agricultural, municipal, and industrial consumptive water uses in the two states studied can be maintained even during a severe, sustained drought. However,

> there would . . . be noticeable and progressive losses of resources dependent on regular minimum stream flows and runoff. Quality of life also would begin to decline with such losses and with the inevitable restrictions on outdoor water use for irrigation of yards, parks and golf courses (Gregg and Getches, 1991, Part II, p.117).

The anticipated effects of drought on consumptive uses are arrayed on Table 2 (Table 5-3 in the Phase I Report). The report cautioned, however, that the present cushion against feeling the effects on drought on consumptive uses would soon be eliminated by growth in demand:

> Ongoing expansion of the population and economy of the area will put new pressures on the system and eventually exceed its capacity. . . . For a while growth can be sustained by using existing supplies more efficiently. . . . But if growth continues, these savings will be consumed and further demand reduction will require alterations in lifestyle. The area must eventually turn to reallocation of existing rights, mostly rights now held by agricultural users. Choices among urban lifestyle, agricultural cutbacks and growth control are bound to be controversial (Gregg and Getches, 1991, Part II, p.10).

Thus, the existing cushion against severe, sustained drought in the Colorado River Basin is diminishing, affording only a temporary window of opportunity for policy makers to anticipate, consider, and plan for the eventual loss of existing flexibilities.

IN-PLACE USES OF COLORADO RIVER WATER

Beginning with the 1922 Compact, the Law of the River has focused predominantly on "consumptive" uses of the water of the Colorado River: apportionment of the river's water is described in terms of "beneficial consumptive use." It should not be surprising, then, that the Phase I Report predicted that natural systems and environmental values would feel the worst effects of a major drought. Nothing in this analysis suggests a different conclusion.

In-place, nonconsumptive uses have been gaining in importance. One of these values – hydroelectric power generation – was recognized as a secondary or "incidental" use for the major federal water storage facilities in the Basin but is, in fact, the major source of revenue returning the substantial cost of these facilities to the U.S. Treasury. The importance of protecting water quality received official recognition in the Colorado River Basin Salinity Control Act of 1974. The water needs of endangered fish species emerged as a major issue beginning in the late 1970s with the implementation of the Endangered Species Act in the Basin. And the importance of the recreational aspects of the Colorado River to the Grand Canyon National Park was acknowledged in the Grand Canyon Protection Act of 1992.

Hydroelectric power generation has not affected the *annual* quantities of consumptive use water available to those holding apportionments of water from the Colorado River, at least in years when flows are normal or above. Rather, the primary effect of hydroelectric generation has been to determine the hourly schedule by which varying amounts of the storage water are released during the year (for example, releasing more water to meet peaking power demands). Concerns have emerged about other values of the Colorado River, such as recreational interests in the Grand Canyon and seasonal flow needs of endangered fishes below Flaming Gorge Reservoir. These concerns have led to changes in the patterns of water storage releases, sometimes interfering with maximization of hydroelectric power revenues. In a prolonged drought, the ability to operate reservoirs in a manner favorable to hydroelectric power generation purposes will be further constrained.

Salinity concentrations in the Colorado River could potentially affect the quantities of water available for

TABLE 2. Possible Effects on Water Supplies of Study Area of Various Length Droughts.

	Surface Waters – California and Arizona	Colorado River: Central Arizona Project	Colorado River: Arizona and California Agricultural Users	Colorado River: Southern California Municipal Users	Los Angeles Aqueduct (Mono Lake and Owens Valley)	California State Water Project	Ground Water: Southern California	Ground Water: Arizona
Phase 1 Short-Term Drought	Reduced	No restrictions in basic deliveries; storage is drawn down.		Curtailed surplus deliveries to MWD	Less surface production	Deliveries continue in amounts comparable to recent years; releases increase for Bay/Delta because less runoff	Increased pumping; less natural recharge; imports relied upon heavily for recharge; storage declines	Less natural recharge; CAP use for recharge declines
Phase 2 Mid-Term Drought	Reduced	No reductions in basic deliveries; heavy drafts on storage; increased salinity effects			Reduced ground water pumping in Owens Valley, less surface production	Reduction of deliveries as shortages must be shared with Central Valley Agricultural users; Bay/Delta water quality problems arise; storage drawn down by releases	Draw-down of aquifer storage; little or no natural recharge; imports less available for recharge; overdrafts begin	Recharge programs end; overdrafts; deeper wells needed; higher power costs
Phase 3 Long-Term Drought	Reduced, less ground water recharge	Cutbacks in deliveries to extent needed to supply California	Reductions in deliveries only after CAP cutoff; reductions shared per Secretary of Interior's discretion		Marked cutbacks in supply as pumping is curtailed	Further reductions of deliveries; runoff fails to replenish storage	Serious overdrafts; all imports needed for direct supply of consumers; saltwater intrusion; production cutbacks; infiltration of contaminant plumes; crop and livestock losses	Damage from overdrafts (subsidence, aquifer collapse, etc.)
			Salinity may be so great water is unusable for irrigation					
		Higher pumping costs as hydropower generation is curtailed						

consumptive use in a period of prolonged drought (Miller *et al.,* 1986). Minute 242 of the U.S.-Mexico International Boundary and Water Commission guaranteed Mexico that the annual average salinity of the Colorado River coming into Mexico will not exceed the salinity measured at Imperial Dam (the diversion point for the Imperial Valley in California) by more than 115 parts per million, plus or minus 30. The United States constructed the Yuma Desalting Plant so that desalted water could be blended with Colorado River water if necessary to meet this obligation. In 1976 the Environmental Protection Agency approved salinity standards for the Colorado River at three locations including Imperial Dam. Because of the substantial natural sources of salinity entering the Colorado River, the salinity added by return flows of diverted water, and the substantial out-of-basin exports of Colorado River water, prolonged drought is likely to increase greatly the salinity concentrations in the remaining flows. In theory at least, consumptive uses of Colorado River water might have to be reduced to meet water quality requirements.

The requirements of the Endangered Species Act may impose the most noticeable constraints in allocating water during the shortages that would arise in the event of a severe sustained drought. The Act protects four endangered fish species in the Colorado River Basin: the Razorback Sucker, the Colorado Squawfish, the Humpback Chub, and the Bony-Tail Chub. Most of the remaining populations of these fishes are found in the Upper Basin, and a recovery plan intended to restore these species to viable condition is in place (U.S. Fish and Wildlife Service, 1993). An important element of the recovery plan is to provide adequate streamflow conditions in essential habitat areas. Moreover, virtually the entire Colorado River has been designated as "critical habitat" for one or more of the endangered fish species (Federal Register, 1994). Under the Endangered Species Act, the Secretary of the Interior has an obligation to protect listed species including these Colorado River fishes. During a prolonged drought, it is probable that the Secretary would be required to take account of the flow-related needs of the fishes as well as consumptive use commitments under the Law of the River. The potential effects of the Secretary's possible alternative courses of action remain to be analyzed.

LEGAL OPTIONS FOR MANAGING A SEVERE SUSTAINED DROUGHT

This assessment suggests that the existing legal and institutional framework governing the Colorado River does not adequately address issues that would be raised by a severe, sustained drought. Indeed, surprisingly little attention appears to have been given this eventuality in the development of the Law of the River, leading to recommendations in 1991 that a new basinwide entity be established to deal with the multiple emerging issues on the Colorado River with participation by a wide range of interests (Getches, 1991). The recommendations of the Phase I Report emphasized improved planning, groundwater storage and management, optimizing management of Colorado River reservoirs, reallocation of existing supplies through transfers and marketing, and management of water demand, as well as formation of a Colorado River basinwide organization.

Where some provision has been made in the Law of the River for addressing water shortages, a number of important ambiguities and uncertainties remain. Priorities have been set for sharing shortages as between the U.S. and Mexico, between the Upper and Lower Basins, and among the states within each of the Basins. However, in some cases, these choices have not been made explicit, nor have they been evaluated in relation to other unquantified demands for the water, such as endangered species protection, recreational demands, or Indian reserved rights.

Except for the Central Utah Project, as recently modified by Congress, and perhaps the Animas-LaPlata Project, it seems unlikely that other major water storage facilities will be constructed in the Colorado River Basin in the foreseeable future. The Central Arizona Project is now virtually complete and is capable of delivering Arizona's full entitlement of Colorado River water. Consumptive demands in the Upper Basin, particularly Colorado, continue to increase at a modest rate. With the river essentially fully developed, it is time for a broad and comprehensive examination of how the Colorado River is being managed and used, and for consideration of changes in the present framework. The ability of this region to respond to a severe sustained drought should be a part of such an investigation.

The 1968 Colorado River Basin Project Act sets out a broad directive to the Secretary of the Interior to develop a "regional water plan" for ensuring an adequate water supply for the Colorado River Basin. Originally envisioned as a study of transbasin water diversion to augment Colorado River Basin supplies, this directive could now be applied to make a basinwide assessment of opportunities for improving overall management of the Colorado River and its many water regulation and diversion facilities. It could be undertaken by the federal government or delegated to a new entity representing federal, state, tribal, and non-governmental interests.

An additional objective of undertaking the statutorily-authorized basinwide water plan could be to identify institutional mechanisms and guidelines by which voluntary interstate agreements altering existing uses of Colorado River water could be made. One such approach, though politically and legally difficult at present, would be to permit a market-driven allocation system to operate within the Colorado River Basin. There is little doubt that a market permitting both intrastate and interstate purchase and sale of allocations to use Colorado River water would provide a more flexible mechanism for meeting changing water demands in the Basin. Presumably such a market would take account of the security of the allocation in times of water shortage, and "higher priority" allocations would move to uses that most value this security of supply.

There have been several proposals in recent years for interstate marketing of Colorado River water (Guy, 1991). For the most part, these proposals have been privately arranged transactions and have been unenthusiastically received by the Basin states. In 1991 California proposed a state-managed water bank in the Colorado River Basin with limited authority to facilitate water transfers (California, 1991). The proposal failed to win support from several affected states.

Interstate transfers or other incentive-based approaches for voluntarily transferring water uses among users in different states within the Colorado River Basin ultimately seem likely. As the water resources of the Basin become scarcer, the economic attractiveness of allowing such transactions will overcome existing obstacles. It seems especially likely that there will be such arrangements made among the states in the Lower Basin. One possible match, for example, is between water-short Nevada and contractors unable to pay for Central Arizona Project water. The Metropolitan Water District of Southern California (MWD) and the Central Arizona Water Conservation District (CAWCD) have already pioneered a creative interstate arrangement by which "surplus" flows in the Colorado River would be stored in underground basins in Arizona for potential future use by MWD and CAWCD (Arizona-California Agreement, 1992).

Efforts to design a regional water plan to facilitate interstate water markets, or to undertake a comprehensive evaluation and use of basin facilities, are constrained by the structure of existing institutions. There is no basinwide forum or other entity for undertaking comprehensive planning or for discussing and solving issues of common interest throughout the region. Creation of such an entity as recommended in the Phase I Report would furnish an institutional framework for facilitating water marketing and water banking (Getches, 1991).

As evidenced by the gradual accretion of the Law of the River, problems with the management of the Colorado River and adaptation to changing conditions have traditionally been addressed on an ad hoc basis. While this demonstrates some flexibility in the Law of the River, the parties involved rarely include all the affected interests. Official federal and state representatives have dominated management and controlled change in the law. Interests such as Indian tribes and environmental groups have been left out and relegated to using legal and political devices to hold up decisions or transactions that may be objectionable to them. Thus, we reiterate the suggestion for the establishment of a basinwide entity as a forum for convening a variety of interested parties to facilitate coping with the threat of drought as well as finding solutions to Colorado River issues (Getches, 1991).

Rigidly applied, the Law of the River is not well suited to deal with the issues likely to arise in the event of a severe, sustained drought. While the probability of such a drought remains unknown, the prospect is generally acknowledged. Even if the probability of a major prolonged drought is low, there is still much to be learned by evaluating the manner in which shortages would be allocated by the existing legal framework. Free of the stress and urgency of imminent drought, the present affords an opportunity to consider whether the priorities imposed and the trade-offs permitted by the legal framework are desirable and acceptable. To the extent the present framework does not promote wise decisions, it is timely to weigh institutional options and to explore creative alternatives to the existing structure.

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INSTITUTIONAL OPTIONS FOR THE COLORADO RIVER[1]

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ABSTRACT: In many interstate river basins, the institutional arrangements for the governance and management of the shared water resource are not adequately designed to effectively address the many political, legal, social, and economic issues that arise when the demands on the resource exceed the available supplies. Even under normal hydrologic conditions, this problem is frequently seen in the Colorado River Basin. During severe sustained drought, it is likely that the deficiencies of the existing arrangements would present a formidable barrier to an effective drought response, interfering with efforts to quickly and efficiently conserve and reallocate available supplies to support a variety of critical needs. In the United States, several types of regional arrangements are seen for the administration of interstate water resources. These arrangements include compact commissions, interstate councils, basin interagency committees, interagency-interstate commissions, federal-interstate compact commissions, federal regional agencies, and the single federal administrator. Of these options, the federal-interstate compact commission is the most appropriate arrangement for correcting the current deficiencies of the Colorado River institution, under all hydrologic conditions.
(KEY TERMS: river basin administration; Colorado River; institutional arrangements; water resources planning; water management; water policy/regulation/decision making.)

INTRODUCTION: THE INSTITUTIONAL CONTEXT OF DROUGHT

When searching for alternative institutional arrangements to improve the Colorado River Basin's ability to cope with drought, it is important to realize that drought raises and exacerbates a host of resource issues that are often already present during normal hydrologic conditions. Conflicts between consumptive water uses and nonconsumptive uses; between environmental and economic objectives; between cities and farmers; between states, basins, and even countries – these kinds of disputes already dot the public policy landscape in the study region. During drought, these conflicts are certain to be intensified, and some new conflicts will undoubtedly arise; but the true significance of drought is that it forces attention be paid to a host of issues that already exist and that will ultimately become critical – even in the absence of drought – as growth in water demands continue.

It is difficult and probably unwarranted, therefore, to try to design institutional arrangements solely for drought response. The kinds of response strategies that are needed – actions such as promoting water conservation and efficient use, reserving water for environmental resources, improving the efficiency of reservoir operations, reallocating water through markets, and improving multijurisdictional cooperation while fostering a "problemshed" orientation in resource management – should be actively pursued in the Colorado Basin even in the absence of drought. Drought may provide the necessary political stimulus for such innovations, but the need for innovation already exists.

In the following pages, a political science perspective is utilized to briefly assess the policy-making and administrative environment of the Colorado River institution, and the dominant mechanisms and patterns of interstate conflict resolution are reviewed. Purely intrastate issues and decision-making processes are beyond the scope of analysis. An investigation follows of the institutional requisites of effective drought coping and of the potential nature of interstate bargaining in the Colorado Basin during drought. The institutional arrangements of the Colorado River Basin are then compared with arrangements seen in other major river basins. (In this study, the terms "institution" and "institutional analysis"

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are defined broadly to include all those formal and informal agreements, processes, forums, and behavioral patterns that collectively describe how resource users, public officials, and other interests interact in the governance, administration, management, and use of the river system.) Given the linkage between drought coping and other facets of resource governance and administration, prescriptions are then offered that are not confined solely to the topic of drought coping, but which offer the potential to improve the ability of the region to respond to a wide range of resource issues under a variety of hydrologic conditions and growth scenarios.

THE CHANGING FACE OF COLORADO RIVER POLITICS

The institutional history of the Colorado River Basin is a colorful and complicated series of interstate conflicts and bargains, and it is the subject of a diverse body of scholarly and popular literature (Hundley Jr., 1986). For several decades, each of the basin states has competed to secure its share of the Colorado. These conflicts have generally taken two forms: apportionment battles, such as those surrounding the ratification of the Colorado River Compact in the Boulder Canyon Project Act of 1928 and the eventual interpretation of that legislation in the *Arizona v. California* (373 U.S. 546, 1963) litigation; and legislative battles for the authorization of water projects and the subsequent appropriation of construction funds. With the notable exception of the Supreme Court action in 1963, the major decisions in the Colorado's history have emerged from the familiar calculus of distributive water development politics. Only by crafting agreements in which all (or almost all) the states could benefit – inevitably at the expense of the federal taxpayer and the natural environment – have the states found the incentive and mechanism to resolve their conflicts. Even the Colorado River Compact, the most celebrated example of interstate cooperation in the basin, became law only when nested within a massive water development bill. Over time, this form of interstate bargaining resulted in the Colorado becoming one of the most heavily regulated and manipulated rivers in the world. It also resulted in the majority of rules collectively known as the "Law of the River."

The Colorado River institution, however, is in a period of transition. The availability of distributive water development legislation has been severely curtailed in recent decades, primarily due to the well-documented economic and environmental abuses of past initiatives (Ingram, 1990; Reisner, 1986). A new paradigm has taken root in the basin, challenging the equity and desirability of additional water development and the continued subordination of "non-market" values to commodity values (Udall *et al.*, 1990). Additionally, the river is fully allocated – in fact, it is overallocated – and most good dam sites have already been developed. As a consequence, few plausible opportunities exist for crafting interstate deals using the familiar legislative approach, for the ability and willingness of Congress to resolve interstate conflicts is limited by the lack of "positive-sum" (and Pareto optimal) solutions. (Positive-sum arrangements are those in which the total net benefits to all parties exceed the net costs. If arrangements allow and require potential "winners" to compensate potential "losers," then all positive-sum deals can be made Pareto optimal – a situation in which no party is made worse off, while some (or all) parties benefit.)

With the changing political climate came a void of interstate conflict resolution mechanisms in the basin. This void has largely been filled by the Secretary of the Interior, the actor most responsible for managing the flow and use of the river at the interstate scale. Many of the most difficult and value-laden choices regarding the use of the Colorado have been delegated to the Secretary in federal legislation, such as the Endangered Species Act and the Colorado River Basin Project Act, and by the Supreme Court in the *Arizona v. California* (1963) litigation. The Secretary holds broad discretionary powers in many areas, including water contracting, reservoir operations, Indian water rights administration, endangered species protection, public lands management, and the allocation of water shortages during droughts – a responsibility of particular importance in this study. Other federal administrators outside of the Interior Department also occupy important decision-making positions in the basin. The region's salinity control program, for example, is primarily overseen by the Environmental Protection Agency, while the Western Area Power Administration, in conjunction with the Federal Energy Regulatory Commission, regulates the distribution and pricing of federal hydropower. Several informal interstate bodies exist for providing input into various regional decisions, including the design of the salinity control program and the annual development of the reservoir operating regime. The ultimate authority to actually make decisions, however, is generally held solely by federal actors.

As the Colorado River institution moves into an era where the management of existing water supplies (rather than new development) is stressed, issues such as reservoir operations, endangered species management, and interstate water marketing have risen to the top of the regional agenda (Getches, 1985). Current efforts to better reconcile hydropower generation with environmental and recreation values downstream of Glen Canyon Dam is an example (NRC, 1987). Conflicts of this nature would be greatly magnified during drought. Even at the intrastate scale, balancing the needs of traditional commodity interests, such as hydropower and irrigation constituencies, with the water needs associated with environmental protection, recreation, and urban water supply is an extremely difficult task. At the interstate scale these challenges are further magnified, placing a premium on the existence of good decision-making processes and forums.

Institutional arrangements for addressing interstate water conflicts should exhibit, at a minimum, six related characteristics (Kenney, 1993). First, the arrangements must recognize a wide range of values and interests, and provide ample opportunities for meaningful representation and participation of all affected parties. Second, the arrangements must encourage practices that protect the integrity of ecological systems, foster respect for natural environments, and recognize environmental limits to growth. Third, the arrangements must facilitate the consideration of a wide range of management options and strategies. Fourth, the arrangements must provide decision-makers and other interested parties with accurate and timely information. Fifth, the arrangements must feature decision-making mechanisms that provide incentives for participation and conflict resolution and that produce clear and enforceable outputs. And sixth, the arrangements must reflect the regional character of water resource problems, and should promote governance and management at the "problemshed" scale – i.e., a geographic region delineated to include the source and expression of specific water problems, rather than a physical construct defined solely by topography or political boundaries.

Historically, the institutional arrangements of the Colorado have done a poor job of satisfying these objectives. Policy has traditionally been formulated by a small network of narrowly-focused water development interests, while the concerns of environmentalists, recreationists, Indians, and other "nontraditional" groups have been systematically excluded (Ingram, 1990). This has resulted in policy initiatives lacking respect for natural environments, indigenous species, native cultures, and nonmarket values (Fradkin, 1981). The institution has also shown a tremendous reliance on structural solutions to water problems, even when better management or regulation of existing uses would produce more cost-effective results – the salinity control program being a recent example (Reisner and Bates, 1990). These biases in the content and process of policy-making have been largely perpetuated by the manipulation of information (NWC, 1973; Reisner, 1986). Information made available to the public and decision-makers is often limited in scope and of dubious quality; and while good information is often unavailable or inaccessible, inaccurate "propaganda" stressing the urgency of new developments often fills local editorial pages, talk shows, and political speeches. These institutional deficiencies have been perpetuated by a policy-making process in which costs and benefits of proposed initiatives have been inequitably disbursed, with excluded parties bearing a disproportionate share of costs (Ingram, 1990).

A diverse group of natural resource professionals are calling for western water policies and decision-making processes featuring greater accountability, creativity, efficiency, and attention to environmental limits and sound economic principles (Feldman, 1991; Long's Peak, 1992; WGA and WSWC, 1991). Many states in the basin are pursuing water management initiatives of this nature, using tools such as the public trust doctrine, public interest provisions in water transfer and appropriation procedures, area of origin statutes, instream flow programs, redefinitions of beneficial use, conjunctive management and groundwater regulation, and a host of related innovations which are collectively reshaping western water codes (MacDonnell *et al.*, 1989; Colby *et al.*, 1989). But at the interstate scale – the focus of this study – progress has been much slower. This lack of progress is often attributed to the region's over-reliance on the federal water development bureaucracy (GAO, 1981; NWC, 1973). Policy initiatives emerging from the Interior Department have historically reflected the construction and commodity-orientation biases of the Bureau of Reclamation, an agency which has been only marginally responsive to the paradigmatic revolution occurring in the West.

In recent years, endangered species concerns have forced the Interior Department to employ a more holistic and balanced perspective in Colorado River matters, especially in the Lower Basin where the U.S. Fish and Wildlife Service is charged with implementing federal endangered species legislation. Under the leadership of Interior Secretary Babbitt, the Fish and Wildlife Service and the Bureau of Reclamation, in conjunction with several other federal and state agencies and private interests, have intensified efforts to develop and implement a variety of management plans designed primarily to protect native fish species harmed by water development. Among the most notable of these efforts is the redesign of the operating regime at Glen Canyon Dam. Although these new initiatives are a welcome addition to the Colorado River institution, the very fact that such efforts are now needed is ample proof that existing arrangements inadequately value and protect the entire spectrum of the river's resources. In order to craft regional policies that more effectively (and proactively) consider public values in water, the arena of decision-making must be modified to feature a broader agenda, better information, greater public accountability, and a more strict adherence to economic principles.

INSTITUTIONAL REQUISITES FOR EFFECTIVE DROUGHT COPING

Promoting Institutional Flexibility

If the potential for drought is factored into all facets of water resources planning, the ability of a region to effectively "drought proof" the collective water system is inevitably enhanced. This simple observation provides a compelling rationale for considering drought in a broad institutional context. Even in progressive institutions, however, major climatic anomalies will eventually necessitate the use of specific drought coping measures. In order to effectively respond to severe sustained drought or other crises, institutional arrangements should allow a wide range of public policies to be utilized. Petak and Atkisson (1982) identify ten general types of hazard-related policies, primarily utilizing strategies based on education, technological innovation, improved system management, and the prohibition of certain activities. These policy types are described in Table 1.

In addition to their divergent strategies, these policy types feature a variety of incentive structures. Public policy scholars generally conclude that policies providing positive incentives – i.e., that utilize the carrot rather than the stick – are preferable to regulatory approaches (Osborne and Gaebler, 1992). The most familiar and effective of the incentive-based approaches for drought coping involve forms of water marketing. Many market strategies can be used to reallocate water during drought, including dry-year options, lease-back arrangements, exchanges among water sources, exchanges of priorities, and water banking (NRC, 1992; MacDonnell *et al.,* 1994). However, in order to ensure that market-based strategies adequately respect environmental and other nonmarket values and are consistent with other water management objectives, it is necessary to nest markets within political frameworks where public policy decision-makers can exercise regulatory and oversight powers.

During drought crises, each of the basin state governors is empowered to exercise broad regulatory powers, including the reallocation of state resources (including water), the suspension of procedural state law, and the issuance of executive orders with the force of law (WGA, 1990). Using powers derivative of state disaster statutes, most western governors in past droughts have established centralized drought organizations or task forces, usually located either in the governor's office or the state agency with primary water resources responsibility (Hathaway, 1991). These bodies often serve as information clearinghouses and help the state fashion multifaceted drought coping programs based on strategies of demand management, supply augmentation, and reallocation. These bodies also coordinate state efforts with federal drought response and recovery programs. An aggressive and well-informed governor can be instrumental in minimizing the impacts of drought.

TABLE 1. Types of Hazard-Related Public Policies.

1. **Action-Forcing Policies.** Adopted by higher level jurisdictions and intended to force loss-reducing activities by lower units and jurisdictions of government.

2. **Attention-Focusing Policies.** Intended to stimulate citizen, group, and governmental interest in losses produced by natural hazards and to promote voluntary state, local, and private action to reduce such losses.

3. **Disaster Recovery Policies.** Intended to assist personal, familial, neighborhood, community, and state recovery from the damages sustained as a result of a natural hazard.

4. **Technology Development Policies.** Focused on development of new knowledge and technology to support hazard mitigating policies.

5. **Technology Transfer Policies.** Focused on transfer of knowledge to consumers, governments, and others, and the use of that knowledge in the long term (as in hazard analysis programs) and the short term (disaster warnings).

6. **Regulatory Policies.** Regulate the decisions and behaviors of private parties and governmental entities to reduce losses associated with exposure to natural hazards.

7. **Investment and Cost Allocation Policies.** Specify conditions governing acquisition and allocation of resources to sustain the activities described above and below. Such policies determine how much will be spent, when, for what purpose, where, and at whose expense.

8. **System Management Policies.** Intended to fix responsibilities, specify the means used, and define the restrictions to be met by hazard mitigation programs.

9. **System Optimization Policies.** Intended to ensure that other policies are effective, compatible with system goals, and internally consistent.

10. **Direct Action Policies.** Authorize direct governmental action to implement a policy, such as physical construction or removal of structures.

Source: Petak and Atkisson (1982).

Crafting an effective drought response becomes significantly more difficult, however, when the drought crisis extends across state lines and involves federally supplied water – conditions that describe the drought under investigation in this study. The interstate reallocation of water resources and the modification of reservoir operating regimes are likely to be central features of an effective regional drought response. At a minimum, these actions – under current institutional arrangements – require the consent and active cooperation of the Secretary of the Interior; and as a practical matter, they require arrangements that facilitate bargaining and coordinated action among the states and the federal government.

When considering the efficacy of different strategies for coping with severe sustained drought, it is important to appreciate that different types of policy responses require different institutional arrangements. For example, while attention-focusing and technology transfer policies can be utilized by administrative bodies lacking regulatory powers, more authoritative entities are necessary to implement regulatory, action-forcing, and system optimization policies. In a comprehensive drought coping program, both voluntary (e.g., market-based) and regulatory approaches are likely to have utility. Given that the majority of Colorado River water is currently allocated to relatively low-valued agricultural uses, it is likely that municipal and industrial demands could be efficiently satisfied by a voluntary water market (Wahl, 1989; Gardner, 1986). Reserving water for environmental purposes (and other public values) is considerably more difficult using market mechanisms and will probably remain a great challenge to policymakers during all hydrologic conditions.

The Untapped Potential of Interstate Water Reallocations

As discussed elsewhere in this volume, the Law of the River does not distribute the burden of water shortages uniformly across the Colorado River Basin. This creates both opportunities and incentives for temporary water reallocations – at both the intrastate and interstate scale – that could potentially be exploited under institutional arrangements that facilitate bargaining, cooperation, and creativity. These institutional objectives are at least partially satisfied by the interstate water bank proposal forwarded by the State of California (1991), which would allow willing rightsholders to temporarily lease water – including water from federal facilities – during crisis situations to other water users throughout the basin. Several other interstate water marketing proposals in the Colorado Basin, including those of the "Ten Tribes" and a recent water bank scheme forwarded by the Bureau of Reclamation, also seek to increase the economic efficiency of water allocations in the region (Colorado River Tribal Partnership, 1992). In theory, market-based reallocations have the potential to significantly increase the drought coping capacity of the basin, as well as having potential utility as a water management tool under normal hydrologic conditions.

Under existing institutional arrangements, interstate water marketing proposals often do not receive serious consideration by the basin states due to the widespread fear of permanently (and inadvertently) losing state water rights currently "guaranteed" in the Law of the River. This concern can be traced to several areas of legal and political uncertainty surrounding all of the interstate water marketing schemes. For example, is marketing even permitted under the Colorado River Compact, federal water contracts and repayment obligations, the Constitution (particularly the Commerce Clause), and other elements of the Law of the River? Should unused entitlements be available for marketing, or should bargains be confined to water supplies currently being consumed? How should pricing be determined, and how should the costs and benefits be allocated? How can the public interest in water resources be protected in a market setting? Perhaps the most critical question is this: how should the market be administered and regulated, if at all? The proposal offered by the state of California called for the states involved to oversee potential deals; the Bureau of Reclamation plan calls for federal oversight; and still other schemes, such as the Roan Creek proposal, are designed to operate in a largely private environment (Gavin and Bettelheim, 1994). (The Roan Creek proposal calls for Nevada to finance construction of a dam near Grand Junction, Colorado, to develop and store water rights held by Chevron Oil and Getty Oil, which would then lease the water to Nevada for consumption in Las Vegas.)

If the institutional barriers to interstate bargaining are removed, several types of market-based water reallocations become plausible in the basin as severe sustained drought progresses. Among the first water users to face cutbacks would be Southern California municipal interests, which rely on surplus flows in excess of the state's 4.4 MAF (million acre-foot) apportionment. In an active market, these high-value uses could potentially be satisfied by arrangements with agriculturists in the Imperial, Coachella, and Palo Verde Valleys, or possibly by bargains with Arizona farmers currently unable to afford Central Arizona Project water. These agricultural regions could also provide water for municipal users in Las Vegas, in both drought and non-drought periods. Several creative intrastate arrangements in California are already being implemented; bargaining at the interstate scale, however, is still in its infancy due to institutional constraints (Wahl, 1989; NRC, 1992).

As a drought worsens, Upper Basin municipal water users might also wish to explore creative market arrangements with irrigators – potentially in both basins – since the Upper Basin would bear the brunt of regional shortages. Implementation of these water transfers, especially those at the interbasin scale, would probably require modifying the rules which coordinate the operation of Lakes Powell and Mead. Even in the absence of explicit marketing, reservoir operations is a likely subject for interstate bargaining during severe droughts since the annual release requirement of 8.23 MAF from Lake Powell can quickly empty the reservoir once inflows decline, causing tremendous hardships to both instream and offstream interests. When factors of salinity, hydropower production, recreation, and endangered species protection are considered jointly with water supply concerns, the potential benefits of more flexible institutional arrangements in the Colorado Basin become obvious – a subject addressed in greater detail by Lord *et al.* (1995) (this volume).

Institutional Options for Interstate Water Resources. Throughout American history, numerous attempts have been made to fashion institutional arrangements for the effective governance and management of multijurisdictional resources (Derthick, 1974; Donahue, 1987). River basins, especially those of an interstate nature, have been among the most active laboratories of intergovernmental experimentation, within which the limits of legal and political feasibility have been explored. One such experiment was the use of the interstate compact device to apportion the flow of a river, a frequently copied innovation pioneered in the Colorado Basin in 1922 (Hundley Jr., 1975).

Since the negotiation of the compact, however, the institutional arrangements of the Colorado have not been the subject of deliberate or progressive reform. The changes which have occurred are primarily derived from incremental and uncoordinated actions, including several awkward attempts to integrate emerging environmental values into an institution founded on the goal of water development. The federal endangered species program is a typical example. The program allows existing patterns of water use to continue until a species extinction is imminent, at which time sudden and potentially draconian measures are mandated. The program is an important addition to the Law of the River, but it is a poor surrogate for arrangements that provide for the consideration of environmental values under all conditions.

One of the most frequent recommendations for improving the content of interstate policy in the Colorado Basin is to formally establish a regional administrative framework which welcomes diverse interests and values in water, and from which more regionally integrated and compatible policy initiatives can emerge (Getches, 1989; GAO, 1981; Bloom, 1986). However, developing institutional arrangements which effectively concentrate authority, activity, and accountability at the problemshed level is a difficult challenge – both conceptually and in practice. The most formal and direct strategy for developing such a "regional institution" is to enlist the aid of a regional organization to order the relationships and activities of non-regional entities at the desired regional scale. These regional organizations are not institutions by themselves but serve as the seeds upon which regional institutions can crystallize and mature. Regional organizations come in many shapes and sizes, and are endowed with widely varying authorities and responsibilities (Donahue, 1987; WRC, 1967). What they inevitably share in common is a hostile political environment, a consequence of political geography and of bureaucratic entrenchment (Derthick, 1974; Ingram, 1973).

Several types of regional organizations exist for the administration of interstate river systems. The most formal of these organizations are generally labeled as "river basin commissions"; many other interstate arrangements, however, are considerably less formal and authoritative, and are not as easily described. In this study, a framework of descriptive terminology is introduced to differentiate among the major organizational forms. Several criteria can be used as a basis for a typology of regional water organizations. Donahue (1987), the Water Resources Council (WRC, 1967), Hart (1971), and Fox (1964) all offer typologies based on "structural" criteria, focusing primarily on differences in memberships and legal foundations. In contrast, Derthick (1974) and Teclaff (1967) offer typologies based on "functional" criteria, distinguishing between organizations with "soft" management functions (e.g., advocacy and coordination) and those with "hard" management roles (e.g., regulation and construction). While both approaches are adequate for descriptive purposes, the comparative analysis of these organizational forms requires a consideration of the interplay between structure and function.

For descriptive purposes, this study presents a structural typology based on two criteria: jurisdictional membership and legal foundation. The jurisdictional membership criterion is utilized to divide regional organizations into three categories: (1) interstate organizations; (2) federal-interstate organizations; and (3) federal organizations. By subdividing these categories based on the legal basis of the organization, a total of seven organizational forms are revealed: *compact commissions* and *interstate* *councils* are interstate organizations; *basin interagency committees, interagency-interstate commissions,* and *federal-interstate compact commissions* make up the federal-interstate organizations; *federal regional agencies* and the *single federal administrator* comprise the federal organization category. The regional arrangements of most major American rivers – including the Colorado – can be grouped into these categories.

Compact Commissions

Interstate compacts are a popular mechanism for allocating rights and responsibilities regarding interstate water resources among the participating jurisdictions. Creating a compact commission to administer the terms of the agreement is traditional but not necessary – e.g., the Colorado River Compact does not utilize a commission, whereas the Upper Colorado River Basin Compact does. Most compact commissions are headed by governor appointees of the participating states and often feature non-voting federal members. (The Upper Colorado River Commission is highly unusual in that it provides for a voting federal member, something that is normally only seen in the federal-interstate compact commissions.) Unanimity (or a close approximation) is the typical decision rule; however, the compact vehicle is sufficiently flexible to support a variety of decision-making arrangements. Budgets and staffing levels are highly variable.

The roles and functions of the compact commission are largely determined by two factors: the nature of the compact, and the degree of authority and autonomy granted the commission. The National Water Commission (NWC, 1973) found that interstate water compacts generally are used in four subject areas: (1) water allocation, (2) pollution control, (3) flood control and planning, and (4) project development (Muys, 1971). Compacts for water allocation are, by far, the most common type in the western United States (McCormick, 1994). The roles and authorities of compact commissions are highly variable, even between compacts addressing similar subject matter. Political viability is the key determinant of a commission's authorities; in general, the more authoritative the proposed commission, the less likely the compact will be successfully ratified (Martin *et al.,* 1960; Derthick, 1974). Given that interstate compacts require unanimous agreement among the basin states and Congress in order to take effect – except in extreme cases such as the Colorado – it is unusual to find a politically viable compact which creates a commission with a high degree of authority. Consequently, most compact commissions have a "soft management" emphasis, concentrating mainly on the collection and dissemination of basinwide information among the affected parties, and acting as a regional advocate in dealings with the federal government (Muys, 1971).

The primary strengths of compact commissions lie in the strength of the compact mechanism itself. Compacts are well established and enforceable mechanisms for addressing interstate disputes, with or without the use of a commission, and can be used in a variety of subject areas. Compact commissions can potentially be vested with broad responsibilities and authorities since they are the joint creation of powerful political sovereigns – i.e., states. The major drawback to the compact commission approach concern the politics of formation – specifically, the requirement of unanimity which often results in "watered down" agreements and weak commissions (Donahue, 1987). Compacts can generally be successfully negotiated and ratified only when needs are pressing and basinwide. Even then, the process of negotiation and ratification can be laborious and time consuming. The Second Hoover Commission found that compacts take approximately nine years on average to successfully negotiate and ratify (Martin *et al.,* 1960). Nonetheless, dozens of compacts and compact commissions dot the institutional landscape, and the compact commission is well established as the most widely recognized form of regional organization for the control of interstate water resources.

Interstate Councils

The second type of interstate organization for the control of regional water resources is the interstate council. This organizational form technically encompasses the interstate compact commission, but it "is generally characteristic of less formal arrangements, established via federal legislation, consistent multistate legislation, multi-state resolution or informal consent" (Donahue, 1987:136). Council members are typically state officials vested with formal authorities and powers independent of the council – most often governors or their appointees. Decision-making usually requires unanimity.

As is true of most organizational forms, the specific roles and functions of interstate councils can only be described in a general manner due to the considerable variability observed in practice. The functions of most councils can be described as "soft" – e.g., coordination, research, and advocacy – with decisions being implemented, if at all, by more established bureaucracies (Donahue, 1987). This *modus operandi* is best illustrated by the typical governor's council, in which the participating governors negotiate and determine regional policies which are implemented by the relevant state agencies. The Council of Great Lakes Governors and the New England Governors' Conference are typical examples (Donahue, 1987; Foster, 1984). The Colorado River Basin Salinity Control Forum could also potentially be classified as an interstate council.

Like compact commissions, interstate councils are a flexible and well established organizational form. Since most councils do not need the level of regional authority only available to the states collectively via the compact mechanism, interstate councils can be relatively easy to establish. If the council members are motivated state governors, a reasonably common situation, significant progress can be made in addressing many regional issues. However, these strengths can also be liabilities. Their generally modest degree of formal authority, combined with a lack of federal membership, prohibits interstate councils from taking aggressive and comprehensive action in many policy areas. Additionally, their dependence on the participation and political resources of the council members can be a liability if leadership is lacking or if the council members face opposition from their state legislatures.

The lines between the interstate compact commission and the interstate council have been blurred somewhat by the Northwest Power Planning Council (NWPPC), which is founded on a combination of federal legislation followed by an interstate compact (Volkman and Lee, 1988). The NWPPC is headed by governor appointees of the four basin states but primarily is charged with regulating the activities of those federal agencies that control the operation of the Columbia River system. This arrangement is New Federalism in the extreme and perhaps will pioneer a new trend in interstate water organizations.

Basin Interagency Committees

The origins of the basin interagency committee – a type of federal-interstate organization – can be traced to the 1940s and 1950s, when federal agencies concerned with river development first organized together with state representatives in a highly informal and ad hoc manner to coordinate their activities (NWC, 1973). The best examples of this organizational form are the so-called "firebrick" committees, formed pursuant to the Federal Interagency River Basin Committee (FIARBC) agreement of 1943. These committees included representatives of the Departments of Interior, Agriculture, and Army; the Federal Power Commission; and later, the Department of Commerce and the Public Health Service (NWC, 1973). Firebrick committees have overseen major developments in several river basins, including the Missouri and the Columbia; however, most of the basin interagency committees formed in the 1940s and 1950s have either been terminated, have "evolved" into different organizational forms, or have become insignificant institutional relicts.

Basin interagency committees are generally formed without any legislative involvement and are totally dependent on the participating agencies for resources and formal authorities. Consequently, they primarily serve as forums for coordination and communication. The committees are primarily federal creations, including state agencies more for coordination than actual decision-making. The rules of decision-making in most basin interagency committees are largely irrelevant, since the committees rarely have statutory authority to implement their decisions. Decisions reached at field-level among the involved agencies must generally be approved by agency directors, governors, the president, and ultimately Congress before major actions are authorized and resources allocated. As a practical matter, securing congressional approval of committee recommendations is best accomplished if decisions are unanimous (Maass, 1951; ACIR, 1972).

The informal and ad hoc nature of the basin interagency committee is the root of its primary strengths and weaknesses (Donahue, 1987). The flexible nature of these committees allows problems to be addressed promptly and in a flexible manner – in theory at least – while remaining relatively dormant and cost-free during calmer periods. The committees also benefit from placing field-level federal resource administrators in direct contact with each other and with state representatives, facilitating the transfer of information and ideas. The primary weakness of this organizational form is that decisions are not binding and generally cannot be implemented without outside approval. Consequently, there is no real incentive or mechanism for reaching agreement on difficult issues. When significant interagency conflicts arise, the basin interagency committee is often bypassed as a conflict resolution vehicle (Maass, 1951; NWC, 1973).

Interagency-Interstate Commissions

The interagency-interstate commissions are descendants of the basin interagency committees and share many of the same characteristics. However, the interagency-interstate commissions have three qualities which justify their inclusion in a separate category: (1) they have a formal legislative basis, (2) they maintain permanent and independent staffs, and (3) they more fully treat states as equals to their federal counterparts. This organizational form was exemplified by the "Title II commissions" established pursuant to Title II of the Water Resources Planning

Act of 1965 and subsequently terminated by presidential order in 1981 (ACIR, 1972; Hart, 1971; Gregg, 1989). These commissions, like basin interagency committees, featured a membership of federal agencies and state representatives, usually governors or their appointees. Funding for the commissions came from both federal and state sources. Each member had one vote, and most commissions made decisions by unanimity. Each commission had an independent chairman appointed by the president, and a vice-chairman selected by the basin states – innovations that helped these organizations to look beyond the narrow water development agendas held by many member agencies. The major functions of the Title II commissions were to coordinate and advocate improved water management policies within their jurisdictions, primarily through the preparation of comprehensive and basinwide water resources plans.

Most of the differences between the firebrick committees and the Title II commissions were overshadowed by the similar political environment in which both organizations were placed. Neither type of organization, in most cases, possessed a sufficiently high level of independent resources and clout to implement their decisions without the cooperation of the participating agencies, Congress, and the Executive. Consequently, both types of organizations generally utilized a decision rule of unanimity and gravitated toward the "soft management" functions of communication, coordination, planning, and information gathering (NWC, 1973; Gregg, 1989). These generalizations do not fit for all the organizations in all instances, but they are sufficiently accurate to consider the two organizational forms to be close relatives despite their different legal structures.

A review of the weaknesses of the interagency-interstate commission format is somewhat redundant at this point, and somewhat irrelevant given that no examples of this organizational form currently exist. Nonetheless, the organizational form does possess several admirable characteristics worth noting. By joining state and federal representatives in a relatively coequal decision-making environment, the interagency-interstate commission provides a conceptually and pragmatically attractive environment for interagency and intergovernmental coordination. The presence of an independent staff and chairman further strengthens this form, providing the promise of a technically competent administrative infrastructure for the collection and dissemination of regionally focused information. These attributes are both supported by the formal statutory basis of interagency-interstate commissions, which provides a degree of status and resources often lacking in basin interagency committees.

Federal-Interstate Compact Commissions

The third type of federal-interstate regional organization is the federal-interstate compact commission (Derthick, 1974; GAO, 1981). Unlike a typical interstate compact which requires congressional consent and ratification but does not require or provide for subsequent federal involvement, a federal-interstate compact includes the federal government on an equal footing with the states – an institutional arrangement which, in theory, resolves many of the constitutional issues of basin management while providing the full resources of the federal government to an organization primarily comprised of state members. The role of the federal government in the terms and administration of the compact is highly similar to that of the basin states in most cases, except that the federal government is exempt from some of the constitutional restrictions on the states and is generally not bound by decisions that the federal representative does not approve. In general, however, the federal-interstate compact commission provides a forum where the states and the federal government interact in a highly equal and cooperative manner, a quality lacking in many institutional arrangements. This factor, combined with the ability to concentrate broad authorities in the organization using the federal-interstate compact mechanism, largely explain the widespread scholarly praise of this organizational form (GAO, 1981; NWC, 1973; ACIR, 1972; WRC, 1967).

The federal-interstate compact commission was pioneered in the Delaware Basin in 1961 and subsequently copied in the Susquehanna Basin in 1970 (GAO, 1981). No other examples exist. Consequently, any generalizations about federal-interstate compact commissions are ultimately a description of these particular organizations. These organizations are governed by an executive committee of state governors (or their appointees) and a federal representative appointed by the president. The rules of decision-making are negotiated as part of the compact and can theoretically vary by subject matter and by the nature of the federal commitment. Forms of majority-rule decision-making are featured prominently in both commissions, although most major agreements are reached through unanimity. The commission's decisions and policies are synthesized into a comprehensive basinwide plan, which is jointly implemented by the administrative branch of the organization and by existing agencies.

Interstate compacts in general provide an extremely strong statutory basis for a commission, a quality which is further enhanced by the formal participation of the federal government. Consequently, federal-interstate compact commissions can potentially be vested with an extremely wide range of authorities and responsibilities, something that is seen in the Delaware and Susquehanna commissions. However, this strong legislative foundation can prove to be a weakness, for "the federal-state compacting process is potentially several orders of magnitude more complex and divisive than that of the interstate compacting process" (Donahue, 1987:132). Failed efforts to enact federal-interstate compacts in the Missouri and New England Basins provide evidence of this challenge of political acceptance.

Federal Regional Agencies

Among the most unusual regional organizations are the two forms of federal organizations: federal regional agencies and the single federal administrator. The federal regional agency is an independent agency of the federal government, created by federal legislation and vested with broad and comprehensive management authority over a specific physical area (Donahue, 1987). Being a federal agency, it is headed by federal representatives appointed by the president and is at least partially supported by federal appropriations. Any further generalizations are impossible, since only one example of this form exists: the Tennessee Valley Authority (TVA).

The TVA, created in 1933, is probably the most famous and widely studied regional water organization in the United States (Selznick, 1966; Martin *et al.*, 1960; Derthick, 1974). It was the sole product of the "valley authority" movement, an ambitious Depression-era effort to minimize interagency and intergovernmental conflicts in water resources management. The TVA, as well as this organizational form in general, is appealing on at least three levels. First, the federal regional agency format allows activities to be focused at the river basin scale rather than at politically defined constructs, such as state boundaries, thereby facilitating an efficient and technically sound approach to water management and development. Second, the high level of formal authority available to the organization from its statutory basis and federal standing allows the federal regional agency to pursue a comprehensive mandate. And third, the integration of planning, development, and management activities within a single agency, combined with the broad mandate, largely eliminates the need for interagency cooperation and bargaining and allows a single organization to implement the programs which it develops.

Perhaps the primary weakness of this organizational form is its irreproducibility. Dozens of proposals to replicate the TVA have been pursued, but all have failed primarily due to strong opposition from existing agencies and to the feared expansion of governmental (especially federal) influence (Fox, 1964). The TVA was a "political accident," arising from a unique period of economic crisis and political chaos (Derthick, 1974:192). In addition to this practical weakness, the federal regional agency form is also troublesome in its subordination of the states and its relative immunity from a system of checks and balances. High authority, when combined with high autonomy, can support innovation equally as well as despotism. Elements of both have been seen in the Tennessee Basin.

Single Federal Administrator

The second type of federal organization for the control of interstate water resources is the single federal administrator, seen in only one major basin: the Colorado (WRC, 1967; Donahue, 1987). The single federal administrator is not a typical "organizational form" and is perhaps better described simply as an institutional arrangement. In any case, the single federal administrator is the "institutional vehicle" utilized in the study region and, as such, deserves close examination.

The single federal administrator label "pertains to any arrangement in which a single, federally appointed administrator is vested with decision-making authority over the use and management of a given resource or set of resources within a specified geographic area" (Donahue, 1987:161). This definition potentially includes court-appointed River Masters used to oversee and implement judicial apportionments but is generally reserved for the Colorado situation. In the Colorado's Lower Basin, the Secretary of the Interior – a presidential appointee – is the single federal administrator, a byproduct of federal legislation and the Supreme Court's decision in *Arizona v. California* (1963). As discussed elsewhere in this volume, the court's landmark decision expanded the already broad discretionary powers of the Secretary to include the authority to allocate shortages among states and individual parties during periods of scarcity, within the poorly defined limits provided in the Colorado River Compact and the Boulder Canyon Project Act. This is a tremendous delegation of authority, especially for a river that is overallocated and extensively utilized and that is apportioned by rules full of technical and legal uncertainties. This newly acquired power of the Secretary has not yet been put into practice in any major episodes, so it is somewhat difficult to decisively evaluate the merits of this institutional arrangement. The potential behavior of the Secretary during severe sustained drought in the Colorado is speculated upon throughout this volume.

The strengths and weaknesses of this organizational form are largely linked to the qualities of authoritative and "top-down" management strategies (Donahue, 1987). In theory, the single federal administrator has the potential to quickly, efficiently, and equitably address difficult and contentious issues in a creative and definitive manner. However, the past performance of the Interior Department in Colorado River politics does not inspire great confidence in the ability of the federal bureaucracy to lead the institution during this era of paradigmatic change and declining water development. Furthermore, this concentration of power in a federal actor is inconsistent with prevailing norms of self-governance and the re-empowerment of the states. Given this element of uncertainty and dubious accountability, the single federal administrator approach has few advocates in the Colorado basin and elsewhere.

CONCLUSIONS AND RECOMMENDATIONS

A Regional Organization for the Colorado

It is not the intention of this study to prescribe substantive solutions to the many policy issues in the institution, but rather to prescribe institutional arrangements that create forums and processes in which these difficult issues can be equitably and efficiently addressed. Ideally, arrangements should be fashioned that promote decision-making based on cooperation and bargaining (as opposed to coercion) among existing rightsholders and other interests, nested within a policy-making framework where accountable decision-makers – preferably at the state or regional level – can ensure that outputs are consistent with long-term regional objectives and public interests. The tremendous economic inefficiencies associated with many water uses in the region provide numerous opportunities for pursuing positive-sum policy objectives through carefully structured markets if transaction costs can be minimized (Wahl, 1989; Gardner, 1986). A process that discourages litigation and does not unduly or authoritatively challenge the existing system of private property rights in water is consistent with these design criteria.

Creating an institutional framework of this nature is probably best accomplished by the formation of a regional water organization with broad responsibilities and authorities. Among the organization's many functions would be overseeing the generation and dissemination of regional information, performing (or sponsoring) research on potential innovations, and coordinating the actions of various state and federal agencies active in the region. The central role of the organization, however, would be to provide a forum where the basin states could establish (and oversee implementation of) regional water management goals and programs, and where interstate bargains could be pursued. In order to support creative resource management at the problemshed scale, the organization's executive body would need to be vested with regulatory authorities in a wide range of subject areas: e.g., the modification of reservoir operating criteria and project purposes, the interpretation of compact and treaty obligations, the consideration of interstate water marketing proposals, the distribution and marketing of hydropower, the pricing and transfer of federally supplied water, the facilitation of Indian water rights negotiations and settlements, the quantification of other federal reserved rights, the design of fish and wildlife protection efforts (including those for endangered species), the formulation of salinity control strategies, and the preparation of risk-avoidance and response plans for drought and flood emergencies. These subjects are currently addressed in a variety of different forums and processes of dubious quality. By unifying these subjects under a single decision-making umbrella founded on the principles of value-pluralism, creativity and flexibility, and a respect for environmental limits, it is likely that initiatives will feature greater integration and compatibility, especially if the organization is supported by an independent technical staff capable of providing accurate and broadly-focused information – a current deficiency of the institution. Purely intrastate issues would be beyond the scope of the organization. On those issues where the organization fails to act, existing rules and decision-making arrangements would remain in effect. Implementation of most programs and policy outputs could remain the jurisdiction of existing bureaucracies, thereby avoiding unnecessary organizational duplication or reorganization.

A primary objective of this proposed innovation would be to formally shift responsibility for the control of the river away from the federal government to a collective of the basin states. This requires that many of the policy-making responsibilities of federal administrators – primarily the Secretary of the Interior – be constrained or completely subsumed by the proposed organization. There are a few federal obligations, however, which should not be delegated to the collective will of the basin states. The protection of federal reserved water rights (including Indian rights), the enforcement of the Endangered Species Act, and the satisfaction of treaty obligations with Mexico are prime examples. The federal government does, after all, own 56 percent of the land area in the basin (73 percent when Indian lands are included), in addition to having financed the major water developments in the region (Weatherford and Brown, 1986). Consequently, the proposed regional organization, while prominently featuring state actors, would need to formally provide for federal participation.

The normative design criteria identified herein, when considered with the functional and structural needs of the proposed regional organization, suggest that the Colorado River institution would benefit most from the creation of a federal-interstate compact commission. This is not a novel suggestion. The National Water Commission (NWC, 1973) and water attorney Paul Bloom (1986), among others, have made similar recommendations. This organizational form, if patterned after the Delaware and Susquehanna commissions, would create a regional policy-making body of basin state representatives (ideally governors) and a federal actor, the Secretary of Interior being an obvious candidate. This would instill a much-needed element of local accountability into many facets of Colorado River politics and would empower state leaders to steer the institution forward during this era of political and paradigmatic change. In those subject areas where there is a compelling need for federal policy-making primacy, the federal representative to the commission could not – as a matter of law – be barred from independently exercising congressionally delegated regulatory powers. This arrangement provides an equitable balancing of state and federal powers within a regional policy-making forum. It is also consistent with funding arrangements which call for contributions from both state and federal treasuries, as well as from water and power users.

The federal-interstate compact mechanism is also desirable due to its ability to concentrate large amounts of power in the proposed organization, including the power to regulate interstate deals – an activity that is normally beyond the independent authority of state governments due to Commerce Clause restrictions. Unlike organizations designed solely to fulfill "soft management" functions (such as advisory or coordinating bodies), the organization proposed for the Colorado would serve as the focal point for regional decision-making. In order to ensure implementation of decisions spanning numerous political and bureaucratic jurisdictions, the organization needs to be endowed with a strong legal foundation – a task for which the federal-interstate compact is ideally suited.

The proposed innovation would not pose a threat to the 1922 Compact or the other basic elements of the Law of the River. Quite the contrary, the organization's organic act would contain a strong affirmation of the basic elements of the interstate apportionment. Other elements of the Law of the River, including environmental statutes and treaty obligations, would also be affirmed. These provisions not only increase the political viability of the proposed organization but also help to establish a framework conducive to interstate bargaining. As market proponents correctly argue, bargaining is constrained whenever legal arrangements imprecisely define rights and responsibilities (Anderson, 1983). A decision rule of unanimity would ensure that no major departures from existing arrangements could occur without the consent of all the basin states and the federal government.

In order to be a fertile arena of decision-making, organizations which rely on a decision-rule of unanimity must be able to craft positive-sum bargains (Wandschneider, 1984). Crafting positive-sum bargains is best accomplished by technically sophisticated management initiatives that improve efficiency (thereby expanding the size of the "pie" to be allocated), or by increasing opportunities for bargaining by expanding the range of issues and options available to the participants. These strategies are most effective when introduced into institutions characterized by inflexible and inefficient patterns of resource use and allocation – qualities seen in the Colorado. Only the most authoritative regional organizations (such as the TVA) have the ability to craft zero-sum initiatives, a fact which makes their creation all but impossible. Initiatives of this nature are best achieved through litigation and some forms of administrative and congressional rule-making.

The Political Environment of Institutional Change

Institutional innovations of the type advocated herein inevitably require disrupting existing bureaucratic arrangements and shifting the distribution of power within an institution. This creates considerable political opposition. Two major strategies exist for overcoming this political hurdle, both of which are applicable to this proposal. First, the magnitude of the institutional disruption can be minimized. The proposed federal-interstate compact commission for the Colorado does not require any fundamental modifications to the interstate apportionment codified in the Law of the River, nor does it require the termination of existing bureaucracies – e.g., federal and state agencies could retain important information gathering and facility operating responsibilities. The proposed innovation would primarily entail a partial shift in policy-making responsibility away from federal administrators to elected state officials and would provide a framework for pursuing market-based and private sector innovations. This is consistent with current national and western norms.

The other major strategy for overcoming the political obstacles of regional organization formation is to opportunistically exploit a crisis or other unusual event temporarily affecting the political climate. Numerous factors could help to quickly produce an environment susceptible to institutional change: a western energy boom could dramatically increase water demands; large Indian water rights quantifications could threaten existing rightsholders; a private – i.e., unregulated – interstate water market could emerge; implementation of the Endangered Species Act, or other environmental legislation, could threaten established water uses; major reclamation reform legislation could be passed by Congress; economic boom or bust could radically affect the agricultural demand for water; a major dam could break; and so on (Kneese and Bonem, 1986). The effects of drought could also serve as a powerful stimulus for change. The creation of the federal reclamation program, for example, was prompted in part by a major midwestern drought in the 1890s (Pisani, 1992). Similarly, drought in the 1920s was at least partially responsible for the passage of the Boulder Canyon Project Act of 1928 and the creation of the Metropolitan Water District of Southern California. As Vincent Ostrom (1953:235) explains, drought provides a valuable political opportunity which should be aggressively exploited:

> ...the sense of anxiety and fear of catastrophe produced by prolonged droughts can be channeled into constructive action by competent political, administrative, and engineering leadership that anticipates the recurrence of droughts and prepares constructive alternatives to meet the water problems that inevitable arise during these periods. Otherwise, these circumstances of fear and drought, accompanied with actual shortages of water, are apt to produce frustration, irresponsible conflict, and occasionally result in quests for magic and panaceas.

Hopefully, the hypothetical drought scenario presented in this study, when coupled with existing political and paradigmatic trends, will help to provide a sufficient stimulus for meaningful institutional reform in the region.

ACKNOWLEDGMENTS

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SOCIAL IMPLICATIONS OF SEVERE SUSTAINED DROUGHT: CASE STUDIES IN CALIFORNIA AND COLORADO[1]

Richard S. Krannich, Sean P. Keenan, Michael S. Walker, and Donald L. Hardesty[2]

ABSTRACT: Survey data collected in the San Joaquin Valley of southern California and the Grand Valley of western Colorado reveal that residents of both areas believe that a severe sustained drought is likely to occur within the next 20-25 years and that their communities would be seriously impacted by such an event. Although a severe sustained drought affecting the Colorado River Basin would cause major economic and social disruptions in these and other communities, residents express little support for water management alternatives that would require significant shifts in economic development activities or in water use and allocation patterns. In particular, residents of these areas express little support for strategies such as construction and growth moratoriums, mandatory water conservation programs, water transfers from low- to high-population areas, water marketing, or reallocations of water from agricultural to municipal/industrial uses. This rejection of water management strategies that would require a departure from "business as usual" with respect to water use and allocations severely restricts the capacity of these and similar communities to respond effectively should a severe sustained drought occur.
(KEY TERMS: drought; social and political; water management; water conservation; water policy/regulation/decision making.)

INTRODUCTION

Human social systems are integrally linked to ecological systems (Duncan, 1961). They are therefore highly vulnerable to major environmental changes, especially if changes are either poorly anticipated or occur extremely rapidly (Little and Krannich, 1989). Both the literature on social response to natural disasters (e.g., Erikson, 1976; Couch and Kroll-Smith, 1991) and that addressing social and economic consequences of large-scale resource developments (e.g., Murdock and Leistritz, 1979; Krannich and Cramer, 1993) have documented the potential for major disruptions when human communities are confronted by conditions that exceed the response capabilities of existing organizations and social structures.

The potential for disruptive consequences is clearly present with respect to periods of severe sustained drought conditions. Although water management systems and water users can generally adapt to short-term periods of water scarcity, response capabilities are likely to be seriously strained when drought conditions are very extreme and of long duration. Even in the case of relatively short-term "normal" droughts, efforts to respond to water scarcity through adaptive mechanisms such as water conservation practices have met with considerable difficulty and mixed success (Hamilton, 1985; Howe *et al.*, 1980). The major adjustments and reallocations that would be required under conditions of severe sustained drought could be expected to create far-reaching social and economic impacts in affected areas. Such impacts would likely be especially severe where water resource availability is already marginal, where demand for water resources is accelerating, or where economic activities and human social structures are highly water-dependent.

The research reported here addresses possible consequences of water scarcity and public response to water management alternatives in two areas of the southwestern United States: the Grand Valley area in western Colorado and the Kern County area of southern California. Throughout the region encompassing these communities, access to water resources is of central importance to local development patterns and the economic and social well-being of area residents (see Brown and Ingram, 1987; Field *et al.*, 1974; Reisner and Bates, 1990; Vaux, 1986). As such, impacts of

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severe sustained drought would be experienced both regionally and at the community level. For example, in areas that are highly dependent on irrigated agriculture, the repercussions of severe and long-lasting reductions in water availability would extend beyond farm operators to encompass a broad spectrum of other economic activities and social organizations linked directly or indirectly to the agricultural sector (see Brown *et al.*, 1992; Easterling and Riebsame, 1987; Gibson, 1984; Schaffer and Schaffer, 1984).

At the same time, it is also important to recognize that significant social and economic consequences of severe, sustained drought would be differentially distributed across segments of affected communities (see Flynn, 1985; Little and Krannich, 1989). Within broadly-defined communities of water users, there are population segments exhibiting highly variable relationships to, dependency on, and vulnerability regarding water resources (see Bradshaw *et al.*, 1983). These relationships, which can be conceptualized as ecological niches within broader water communities (Hardesty, 1977), need to be taken into account when attempting to understand the potential social consequences of drought and the acceptability of various policy or management alternatives that might be implemented to prevent or mitigate water shortages.

RESEARCH APPROACH

Study Areas

The research summarized here involved a comparative case study approach designed to address some of the social implications of water scarcity conditions that may emerge under both "normal" drought and a hypothetical severe sustained drought. This hypothetical drought scenario, based on hydrologic models involving tree ring studies designed to reconstruct pre-historic flows in the Colorado River system (Tarboton, 1993), was characterized as extending for up to two decades, a far longer time frame than any previously-experienced drought periods. The research was conducted in two very different types of water community settings – an area that relies primarily on water withdrawals from the main stem of the upper Colorado River, and an area heavily dependent on both ground water reserves and imported surface water supplies.

The Grand Valley study area, which is centered around the city of Grand Junction in western Colorado, is highly dependent on the availability of Colorado River system water for agricultural, industrial, and municipal uses. Although this area did experience some effects of the 1986-92 drought that engulfed much of the western U.S., water supplies derived from the main stem of the river and most tributary rivers and steams generally remained adequate to maintain normal use patterns. More significant shortages were experienced in some outlying areas reliant on water from smaller tributary streams.

Despite the absence of major area-wide water shortages during this recent drought, water supply issues were (and continue to be) a focus of considerable public interest in the Grand Valley area. Long-term conflicts over diversion of water supplies from western Colorado to the state's east-slope metropolitan areas have created a sociocultural and political context in which water rights and water supply issues are frequent topics of debate. Growing regional demands on Colorado River flows, including increased demands from the lower basin states, have heightened area residents' levels of awareness and concern about their vulnerability to drought.

The Kern County study area encompasses the Bakersfield metropolitan area and much of surrounding Kern County in California's San Joaquin Valley. Although not directly dependent upon water flows in the Colorado River Basin, the area is indirectly linked to conditions in the Basin due both to geographic proximity and hydrologic linkages with areas of southern California that do rely more directly on Colorado River water.

Unlike the Grand Valley area, the Kern County study area is dependent on a highly complex water supply and delivery system that relies on both diversion of surface water from distant sources in the Sierra Nevada range and northern California and extensive ground water pumping. Expanding water demands associated with urban-area development pressures and irrigation use by large-scale commercial agriculture have made this area extremely vulnerable to water scarcity (see Vaux, 1986). The 1986-1992 drought resulted in severely curtailed supplies of water imported from the north as well as significant reductions in ground water reserves as pumping was increased to make up for reduced surface water supplies (see Kern County Water Agency, 1992). While surface water allocations to municipal and industrial users were cut by as much as 70 percent, municipal systems were able to rely on increased ground water pumping and the purchase of additional allocations from northern California. Although water conservation programs were implemented, restrictions on residential and commercial water use were generally modest. In contrast, agricultural users experienced reductions ranging as high as 100 percent of their normal irrigation allocations, and the high cost of purchasing additional allocations from the north proved prohibitive for most agricultural operators (Kern County Water Agency, 1992).

Data Collection Procedures

Data collection procedures involved administration of highly similar self-administered sample surveys in each study area. In the Kern County study area, multi-wave mail survey procedures (see Dillman, 1978) were used to deliver questionnaires to a probability sample of 1,053 households in early 1992. Sample households were drawn from a composite sampling frame derived from local municipal water utility customer listings, Bakersfield telephone directory listings, and listings of agricultural water users provided by several irrigation districts (for details on sampling procedures, see Keenan, 1993). A total of 618 usable questionnaires were completed and returned by adult decision-makers in the sampled households, representing an overall response rate of 59 percent.

In Grand Valley, surveys were administered to a probability sample of 200 households drawn from listings of residential properties maintained by the Mesa County assessor's office. Using a personalized drop-off/pick-up technique, questionnaires were delivered to an adult decision-maker in each of the sampled households. A total of 147 completed surveys were returned, representing an overall response rate of 74 percent. A summary of respondent characteristics for both study areas is presented in Appendix 1.

Analysis Approach

As a first step in the analysis, survey responses were compared in order to ascertain possible similarities and differences across water user communities. This comparative analysis focused on residents' perceptions of current and possible future drought conditions, levels of perceived vulnerability to water scarcity, and views about the relative acceptability of various management strategies and alternatives for preventing or mitigating future water shortages. In addition, multivariate analyses were conducted to address the question of differential response among various water user niches, as represented by respondents' sociodemographic attributes and their attitudes and perceptions about water resource conditions.

FINDINGS

Current Drought Perceptions

Consistent with the nature of 1986-92 drought experiences outlined previously, residents of the Kern County study area were substantially more likely to consider recent water shortages to be a serious problem in their area than were residents of the Grand Valley area. As depicted in Figure 1, on a response scale ranging from 0 ("Not At All Serious") to 10 ("Extremely Serious"), approximately 75 percent of responses from the Kern County area were on the "serious" side of the scale (responses in the 6-10 range); the mean response was 7.2. In contrast, the mean response in the Grand Valley area was only 4.5, and just 30 percent of responses were above the scale midpoint.

In both study areas, respondents were substantially less likely to report that their own households had been seriously affected by recent drought conditions. As indicated in Figure 2, just 9 percent of responses from Grand County respondents were on the "serious" side of the 0-10 scale midpoint, and the mean response value was just 1.8. In the Kern County study area, the mean response was higher at 3.8, but still only about one-fourth (27 percent) of responses were in the scale range (6-10) that would suggest relatively serious effects of water scarcity on respondents' households.

In general, these response patterns indicate the relatively high degree of success that both areas experienced in adapting to water scarcity during the 1986-1992 drought period. Despite very substantial reductions in Colorado River system flows through the Grand Valley and in surface water allocations to Kern County, both areas were substantially buffered from experiencing widespread negative impacts by the ability to draw upon stored water reserves – Colorado River system impoundments in the case of Grand Valley, and ground water reserves in Kern County. Even though the 1986-1992 drought was serious and of unusually long duration, the buffering effects of these reserves allowed most water users to experience limited inconveniences rather than major adverse effects.

Perceptions of the Likelihood of Severe, Sustained Drought

In an attempt to link the analysis of social consequences with the broader study of severe sustained drought, the survey questionnaire presented respondents with a scenario describing a hypothetical severe

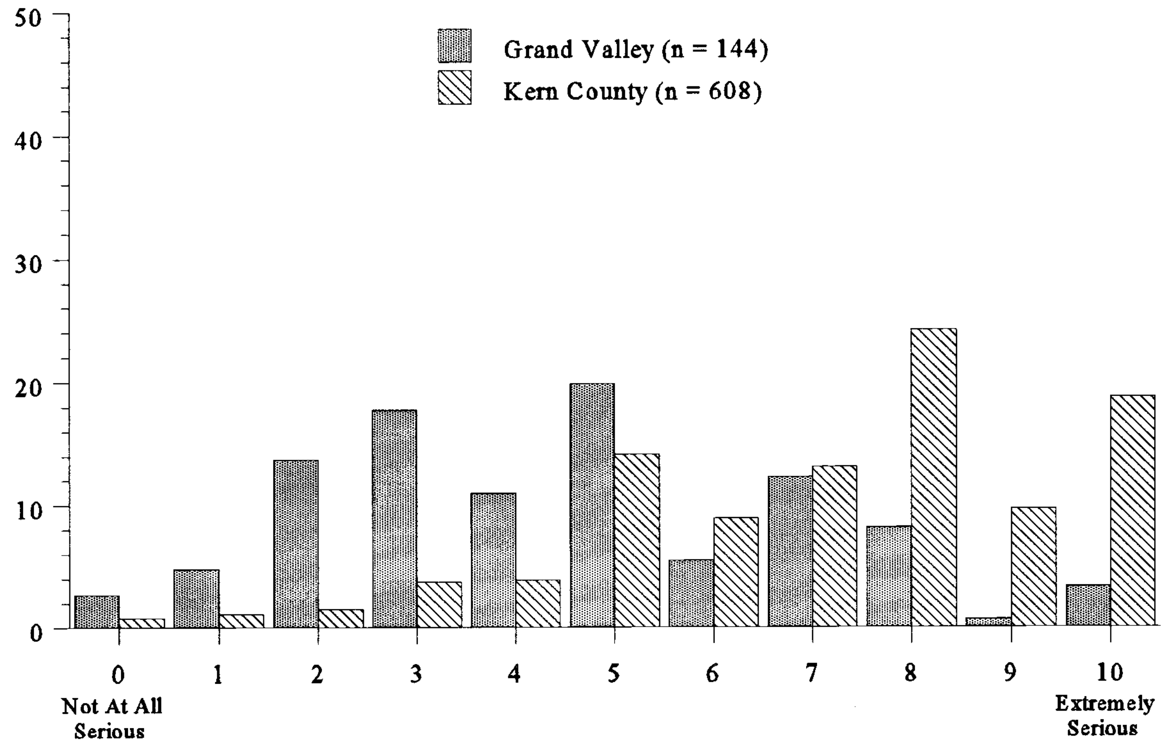

Figure 1. Perceived Seriousness of Recent Water Shortage in Grand Valley, Colorado, and Kern County, California, Study Areas (percentages).

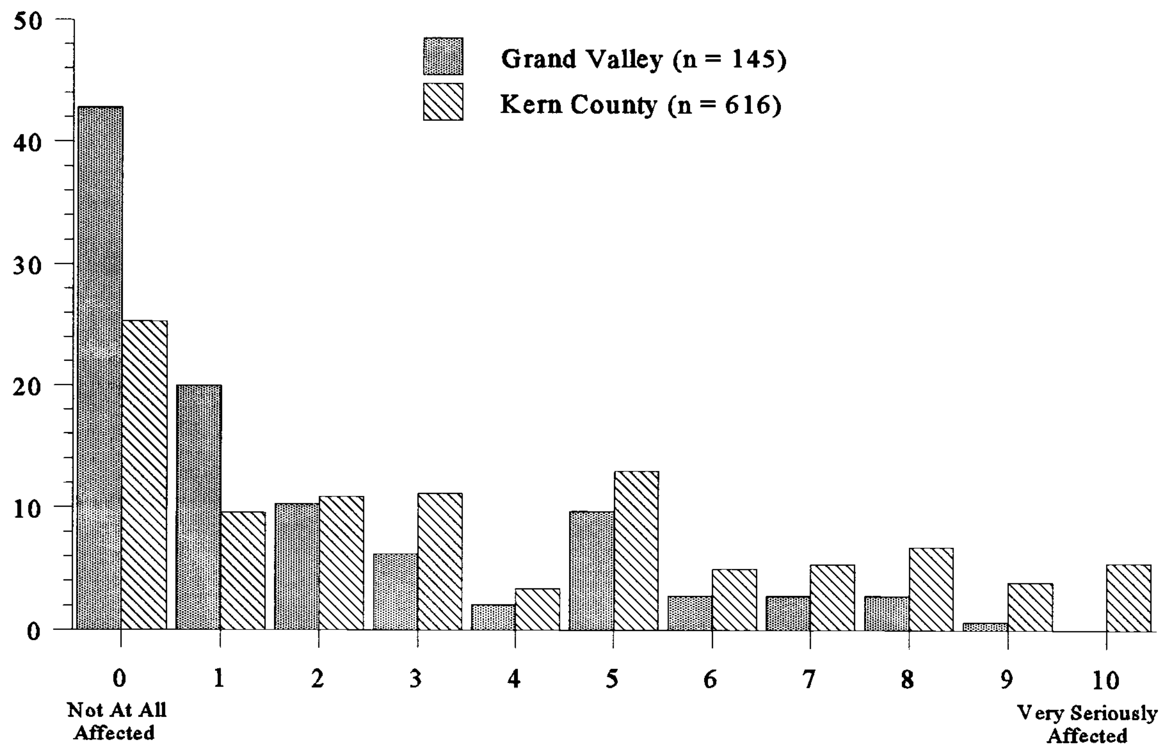

Figure 2. Extent of Negative Effects on Household Resulting From Recent Water Shortages in Grand Valley, Colorado, and Kern County, California, Study Areas (percentages).

long-term drought that would "last for an uninterrupted period of about 20 years." The scenario further indicated that the "total available supply of water in your local area would be more severely limited than has ever occurred before. Water from surface supplies such as rivers, reservoirs and canals would be reduced, and community water systems would be able to supply only one-half of the amount of water that they can provide to users under normal conditions."

Residents of both study areas tended to believe that such a severe sustained drought is only moderately likely in the near term but that there is a substantial likelihood that such conditions will be experienced within a more extended time frame. As indicated in Figure 3, most respondents in both the Grand Valley and Kern County study areas considered it only moderately likely that a severe sustained drought would impact their area within the next five years. In contrast, a majority of respondents in both study areas considered it highly likely that such drought conditions will affect their areas within the next 20-25 years (Figure 4). Although recent water shortage experiences have generally been more negative in Kern County, residents of the two study areas expressed similar views regarding the likelihood of a severe sustained drought within this time period.

Multiple (ordinary least-squares) regression analyses were conducted to address the question of how perceptions about the likelihood of severe sustained drought might be differentially distributed across various types of residents who might occupy differing water user niches. Several sociodemographic variables corresponding to respondents' personal and household characteristics, as well as respondents' views about the seriousness of recent water scarcity problems, were included as potentially important predictors of the perceived likelihood of future severe sustained drought within the next 20-25 years. The results of this part of the analysis, which are reported in Table 1, indicate that these variables were generally not useful in predicting the perceptions of the likelihood of severe drought. For the Grand Valley sample, the nine independent variables jointly accounted for very little of the variation in the dependent variable, as indicated by R^2 values. Only perceived seriousness of recent water scarcity and occupation exhibited substantively important partial associations with the perceived likelihood of severe drought (it would be misleading to base comparisons strictly on statistical significance of coefficients because of sample size differences; therefore, standardized regression coefficients with an absolute value of at least 0.15 are considered to represent nontrivial relationships). In the Kern County study area, the independent variables exhibited similarly weak predictive power. Although several of the partial

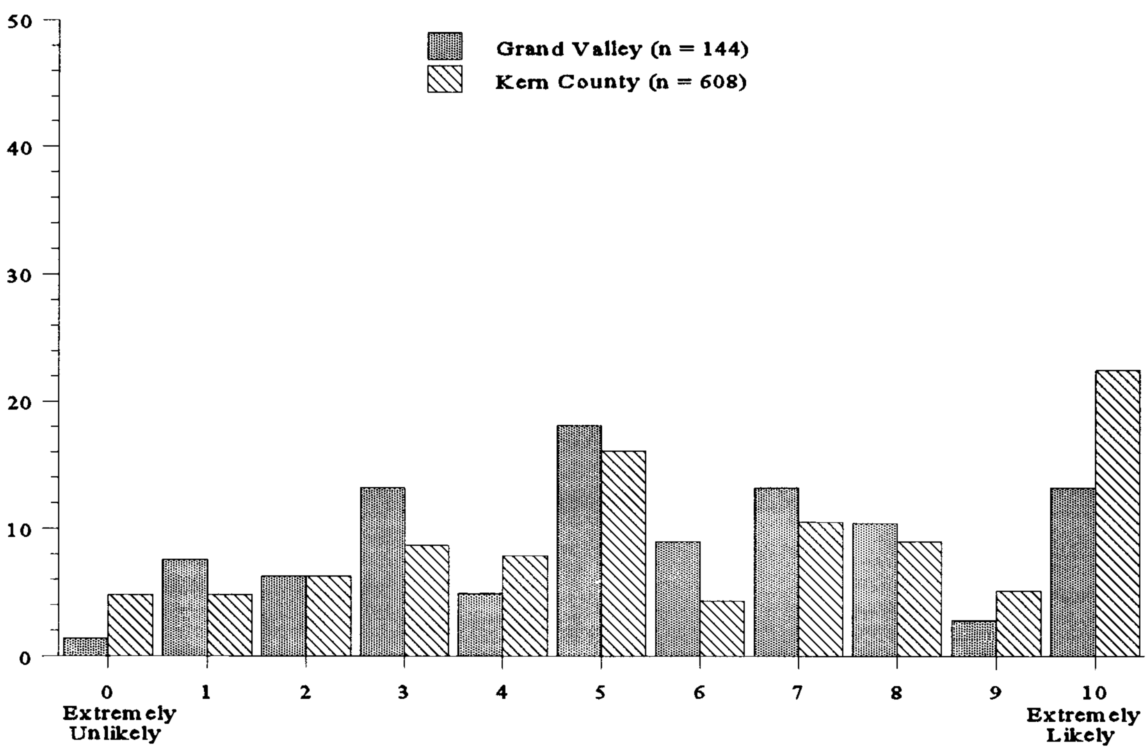

Figure 3. Perceived Likelihood of Severe Sustained Drought Conditions Within the Next Five Years in Grand Valley, Colorado, and Kern County, California, Study Areas (percentages).

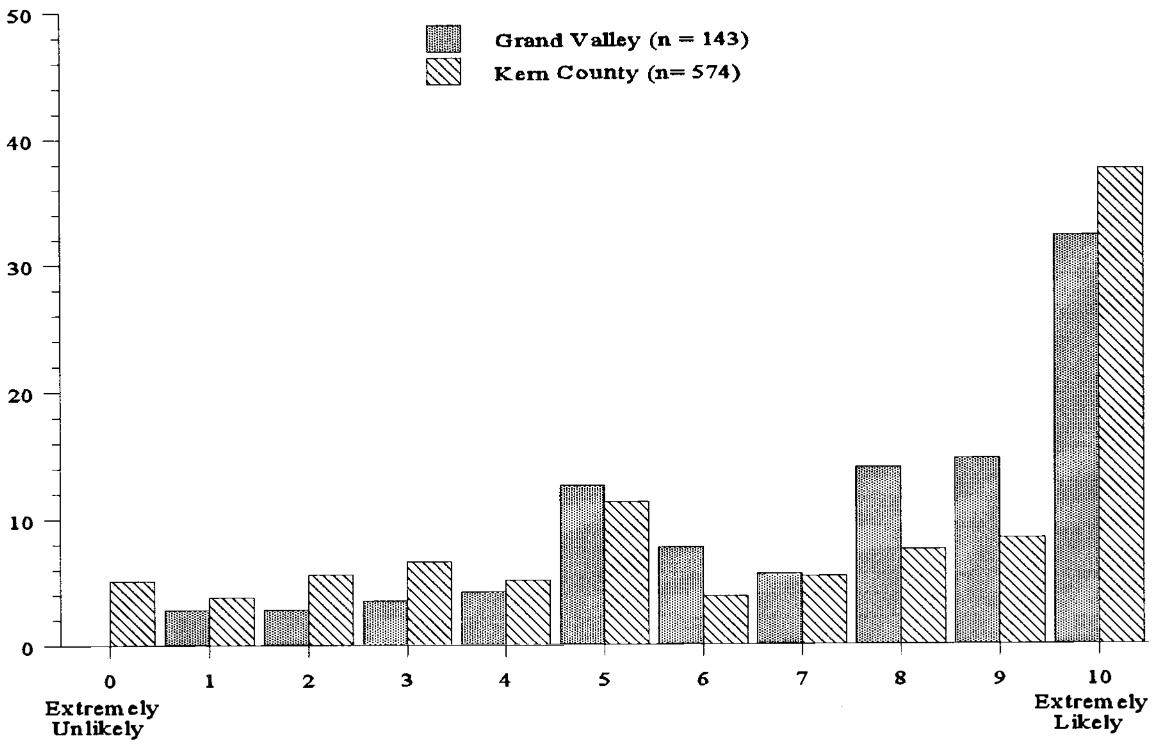

Figure 4. Perceived Likelihood of Severe Sustained Drought Conditions Within the Next 20-25 Years in Grand Valley, Colorado, and Kern County, California, Study Areas (percentages).

TABLE 1. Multiple Regressions of Respondent Sociodemographic Characteristics and Perceived Seriousness of Recent Water Scarcity on Perceived Likelihood of Severe Sustained Drought During the Next 20-25 Years (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age (years)	–.081	–.058
Education (0=high school or less; 1=post high school)	–.001	–.028
Gender (0=female; 1=male)	–.050	–.101**
Length of Residence in Area (years)	.089	.121**
Occupation (1=agriculture; 0=other)	–.158	.083*
Home Ownership (1=own or buying home; 0=other)	.107	.008
Household Size (no. of persons)	.060	–.009
Household Income (8 categories)	–.057	.054
Perceived Seriousness of Recent Water Scarcity	.177*	.163**
R^2	.079	.064

**$P \leq .05$.
*$P \leq .10$.

coefficients attained statistical significance (due primarily to the larger sample size in the Kern County study area), only perceived seriousness of recent water scarcity exhibited a substantively important relationship with the dependent variable.

Thus, in both study areas, residents who perceived recent water scarcity to be a serious problem tended also to believe that severe sustained drought conditions are likely to occur in the future. Also, there was little evidence that perceptions of the likelihood of future severe drought tend to vary meaningfully across categories of residents defined by personal or household sociodemographic attributes.

Concerns About Vulnerability to Severe Sustained Drought

Kern County respondents were somewhat more concerned about the vulnerability of themselves and the broader community to severe sustained drought than were residents of the Grand Valley study area. This is likely due in part to the considerable importance of irrigated agriculture to the broader economic fortunes of Kern County. As depicted in Figure 5, concern about the potential for personal financial losses from severe sustained drought was lower in Grand

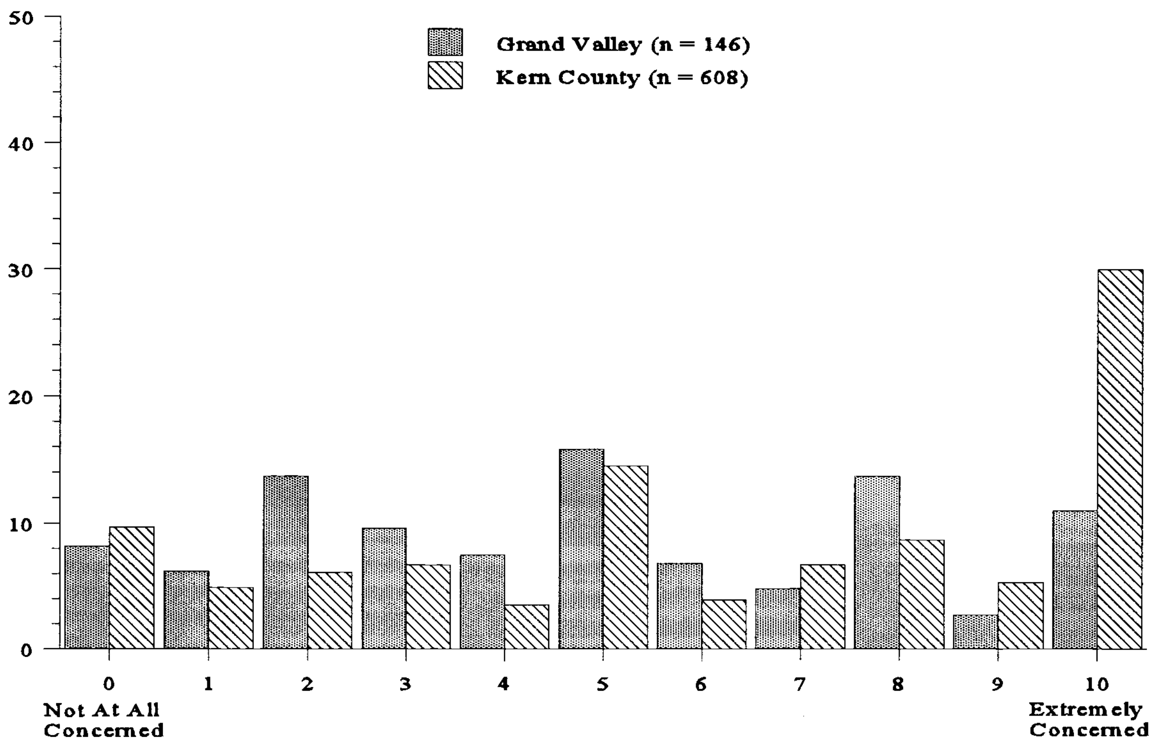

Figure 5. Levels of Concern About Potential for Personal Financial Losses From Severe Sustained Drought in Grand Valley, Colorado, and Kern County, California, Study Areas (percentages).

Valley (mean = 4.9) than in the Kern County study area (mean = 6.1). Similarly, Figure 6 indicates that a higher proportion of Kern County respondents anticipated "very serious" effects on local area economic opportunities than was the case among Grand Valley respondents.

Multivariate analyses designed to predict variation in these two measures of perceived vulnerability to severe sustained drought are presented in Tables 2 and 3. As with the multivariate analysis focusing on the likelihood of severe drought, these analyses incorporated both sociodemographic characteristics and perception measures as independent variables.

Table 2 summarizes regression results incorporating perceived vulnerability to personal financial loss as the dependent variable. Unlike the analysis of perceived likelihood of severe drought, several variables exhibit substantial predictive power in explaining variation in this dependent variable. Considering first the Grand Valley sample, we find that in combination the sociodemographic and perceptual measures account for about 35 percent of the variation in perceived personal vulnerability. Substantively large partial coefficients associated with occupation, household size, and perceived likelihood of severe drought suggest that perceived personal vulnerability is greatest among persons who are involved in agriculture, have large households, and perceive a high likelihood of future severe drought. Results for the Kern County study area indicate a similar level of overall predictive power, with partial coefficients indicating that perceived personal vulnerability tends to be highest among males, persons engaged in agriculture, those who perceive recent water scarcity to be serious, and those who perceive a high likelihood of future severe drought.

Table 3 presents a similar set of regression analysis results, focusing on concern about local area economic effects from severe sustained drought as the dependent variable. In the Grand Valley study area, the overall explained variation is fairly high (R^2 = 0.29), although only the perceived seriousness of recent scarcity and perceived likelihood of severe drought exhibited substantively important partial associations with concerns about area economic effects. These same two variables are the only substantively important predictors in the Kern County study area, although the overall level of explained variation is substantially lower there (R^2 = 0.15) than was observed for the Grand Valley data.

These results suggest that perceived personal vulnerability to severe sustained drought is differentially distributed with respect to both perceptual measures of recent drought severity and future drought probabilities and some sociodemographic characteristics such as occupation and household size. Concerns

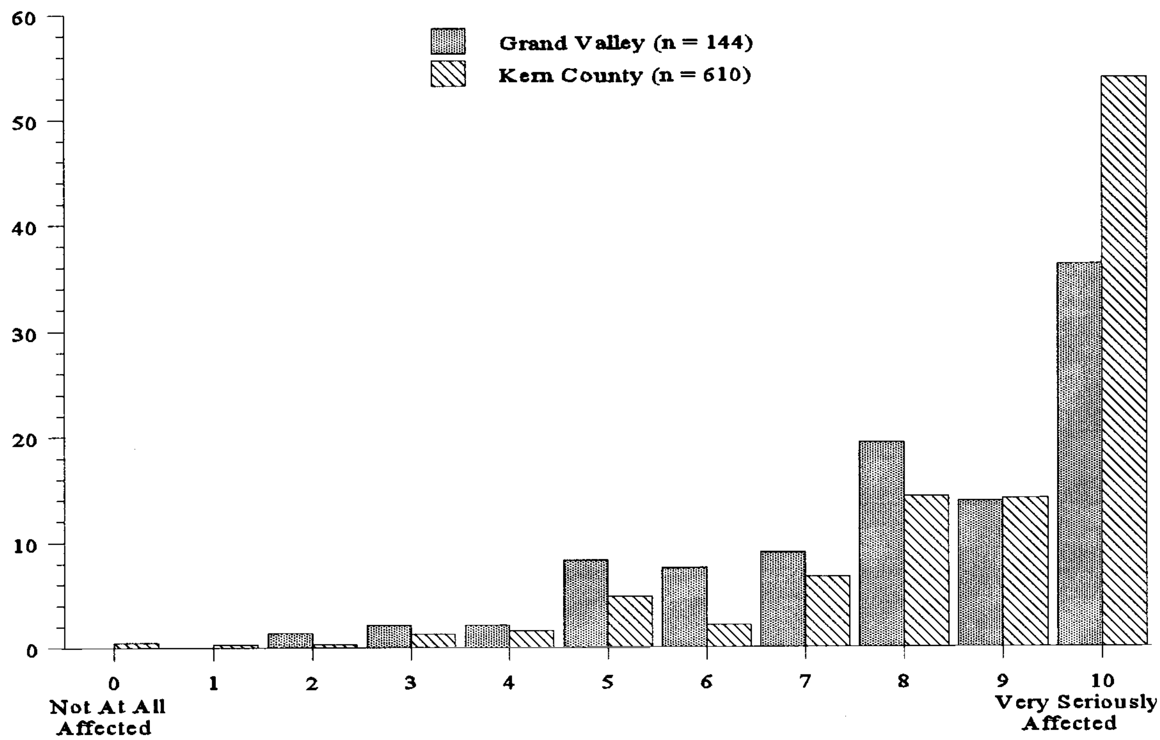

Figure 6. Anticipated Levels of Severe Sustained Drought Effects on Overall Local Area Economic Opportunities in Grand Valley, Colorado, and Kern County, California, Study Areas (percentages).

TABLE 2. Multiple Regressions of Respondent Sociodemographic Characteristics, Perceived Seriousness of Recent Water Scarcity, and Perceived Likelihood of Severe Sustained Drought on Concern About Vulnerability to Personal Financial Loss Under Severe Drought Conditions (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age	.136	–.070
Education (high school or less/ post high school)	.116	.033
Gender	–.024	.119**
Length of Residence in Area	–.061	.095**
Occupation (agriculture/other)	.408**	.287**
Home Ownership (own or buying home/ other)	–.025	–.026
Household Size	.378**	.079*
Household Income	.057	.077*
Perceived Seriousness of Recent Water Scarcity	.128	.165**
Perceived Likelihood of Severe Sustained Drought	.301**	.256**
R^2	.357	.311

**P ≤ .05.
*P ≤ .10.

TABLE 3. Multiple Regressions of Respondent Sociodemographic Characteristics, Perceived Seriousness of Recent Water Scarcity, and Perceived Likelihood of Severe Sustained Drought on Concern About Local Area Economic Conditions Under Severe Drought Conditions (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age	.036	–.058
Education (high school or less/ post high school)	–.017	.083*
Gender	–.133	.018
Length of Residence in Area	.012	.041
Occupation (agriculture/other)	.100	.057
Home Ownership (own or buying home/ other)	–.028	.083*
Household Size	.138	–.037
Household Income	.039	.005
Perceived Seriousness of Recent Water Scarcity	.156*	.256**
Perceived Likelihood of Severe Sustained Drought	.440**	.178**
R^2	.291	.150

**P ≤ .05.
*P ≤ .10.

about area-wide drought vulnerability also are associated with perceptions of recent and future drought but appear to be less closely related to sociodemographic characteristics.

Acceptability of Alternative Management Strategies

Although many water supply and delivery systems appear capable of adapting successfully to "normal" drought conditions, adaptation to severe sustained drought conditions would require unprecedented shifts in water system management procedures and water policies. However, resource management and policy decisions are often constrained by the degree to which they are deemed acceptable by various public interests. Consequently, it is important to examine the relative acceptability of various response strategies that might be considered when addressing water scarcity problems.

One type of response strategy involves establishing priorities for allocating available water supplies during periods of scarcity. Survey respondents were therefore asked to consider the degree to which various types of users should be given priority in receiving water allocations under conditions of severe sustained drought. As depicted in Figure 7, mean response values were generally quite similar for the two study areas. In both areas, respondents indicated that highest priority should be given to users requiring irrigation supplies for permanent agricultural crops such as fruit trees or vineyards. Existing residential households and irrigators growing nonpermanent crops were also considered to be high-priority users in both study areas. New residential developments and recreational water users were viewed as

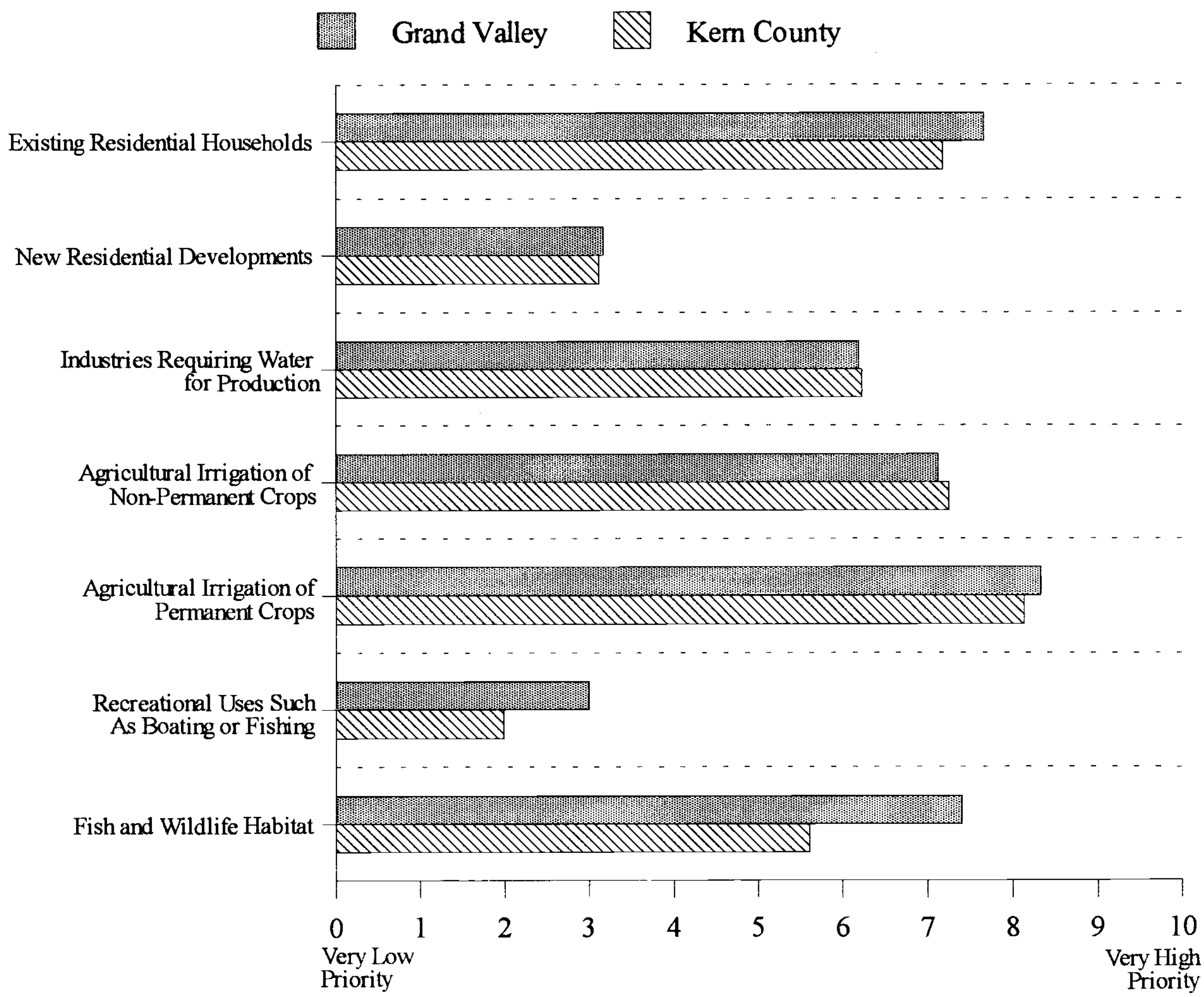

Figure 7. Mean Response Values Representing Attitudes About Priorities for Allocation of Water Supplies During Periods of Severe Sustained Drought, Grand Valley, Colorado, and Kern County, California, Study Areas.

having low priority for water allocations in both study areas.

Another category of response alternatives to water scarcity problems involves various approaches to increasing water supplies, decreasing demands, or reallocating water use to different categories of users. In both study areas, respondents were asked to evaluate the acceptability of nine different management strategies for addressing water scarcity problems. These ranged from approaches involving relatively little personal sacrifice or change from "business as usual" (e.g., implementation of voluntary education/conservation programs) to alternatives involving potentially radical departures from current water management practice (e.g., mandated reallocations of water from agricultural to municipal/industrial uses).

Response means summarized in Figure 8 reveal that Grand Valley and Kern County residents provided very similar evaluations about the relative acceptability of various alternatives involving these types of response. In both areas, the three "most acceptable" alternatives were voluntary education/conservation programs, use of water-saving irrigation technologies, and construction of new water storage/delivery systems – all "business as usual" strategies that would be unlikely to seriously disrupt the water niche structures of the study areas.

Respondents were considerably more ambivalent about approaches that would potentially impose personal or area-wide costs, such as construction moratoriums/growth limitations or mandatory conservation enforced by fines or penalties. Grand Valley respondents in particular were opposed to either within-state or across-state transfers of water supplies from low-population to high-population areas. This finding is hardly surprising, given the existence of long-standing tensions over transfers of water from western Colorado to the east-slope metropolitan areas of

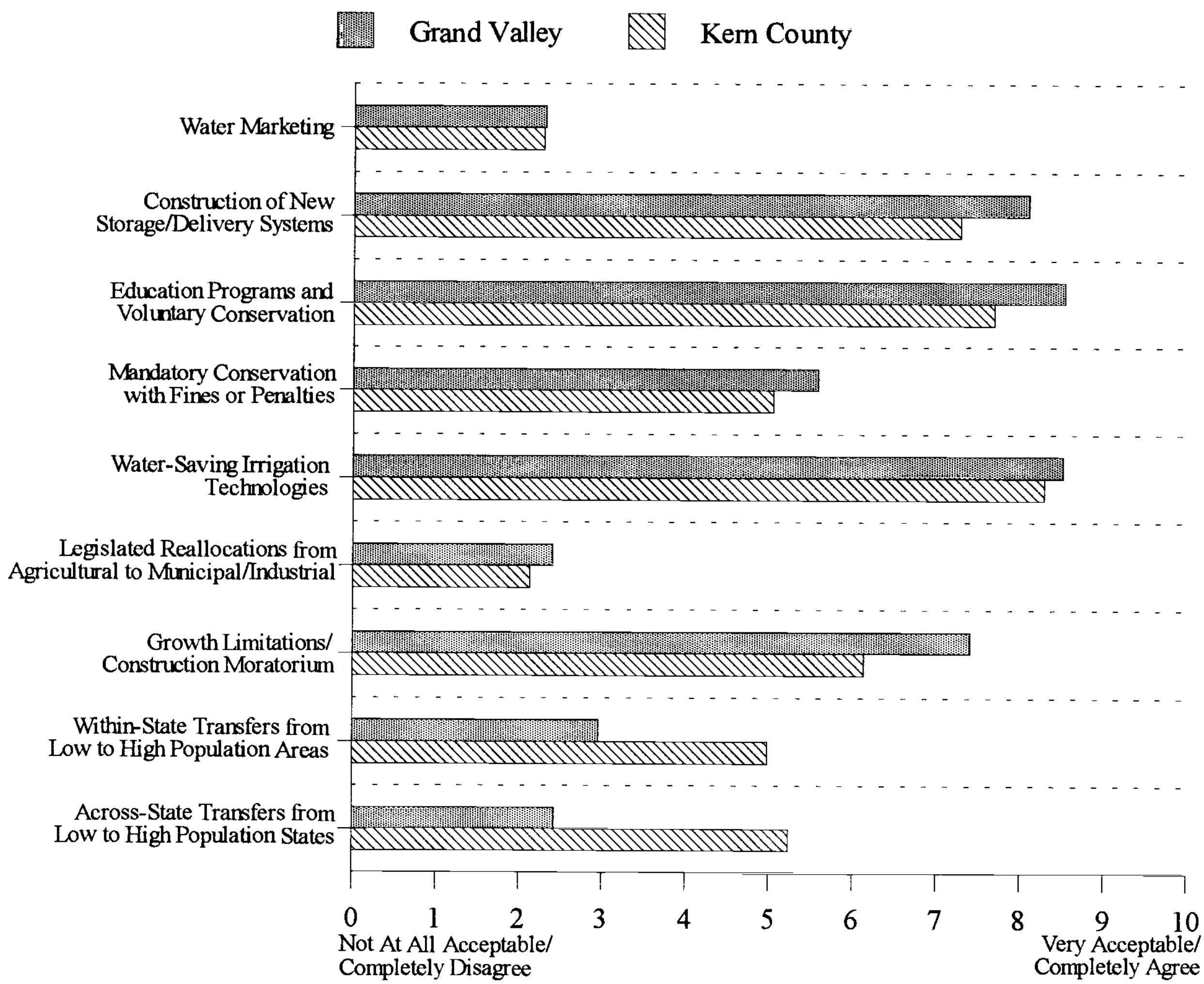

Figure 8. Mean Response Values Representing Acceptability of Various Water Scarcity Response Strategies, Grand Valley, Colorado, and Kern County, California, Study Areas.

the state. Responses to such transfers were more evenly mixed in Kern County, an area that currently benefits from transfers of water from the north but is also vulnerable to growing demands for water from the Los Angeles area to the south. Respondents from both areas expressed considerable opposition to either water marketing or legislated reallocations of water from agricultural to municipal/industrial uses as alternatives for addressing water scarcity problems.

Additional multiple regression analyses were conducted to address the question "who supports the more 'radical' management response alternatives?" Results of these analyses are presented in Table 4 (construction moratoriums/growth limits), Table 5 (mandatory conservation enforced by fines), Table 6 (water marketing), and Table 7 (legislated reallocations from agriculture to municipal/industrial).

As indicated in Table 4, in the Grand Valley the variables exhibiting non-trivial partial associations with acceptability of growth controls were education, gender, home ownership, household income, perceived likelihood of severe drought, and perceived personal vulnerability to severe drought. These coefficients indicate that, other things being equal, acceptance of growth controls is higher among those with post-high school education, men, homeowners, those with lower household incomes, those who believe future severe drought is likely, and those less concerned about personal vulnerability to severe drought. In Kern County, statistically significant but small partial coefficients were observed only for length of residence, occupation, and perceived likelihood of severe drought, and overall explanatory power was very low.

Results summarized in Table 5 indicate that, in the Grand Valley, acceptance of mandatory conservation tended to be greater among those who reported shorter length of residence in the valley, owned or were buying their homes, had larger households, reported post-high school education, and were older. In Kern County, acceptance of mandatory conservation was

TABLE 4. Multiple Regressions of Respondent Sociodemographic Characteristics, Perceived Seriousness of Recent Water Scarcity, Perceived Likelihood of Severe Sustained Drought, and Perceived Vulnerability of Self and Area to Severe Drought on Acceptability of Growth Controls and Development Limitations to Address Water Scarcity Problems (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age	.129	.002
Education (high school or less/ post high school)	.243**	–.053
Gender	.201**	.053
Length of Residence in Area	.034	.102*
Occupation (agriculture/other)	.120	.072**
Home Ownership (own or buying home/ other)	.149	–.057
Household Size	.036	–.028
Household Income	–.207**	.006
Perceived Seriousness of Recent Water Scarcity	.070	.010
Perceived Likelihood of Severe Sustained Drought	.209**	.158**
Perceived Personal Vulnerability to Severe Drought	–.211**	–.067
Concern About Area Economic Effects of Severe Drought	–.011	.054
R^2	.209	.061

**P ≤ .05.
*P ≤ .10.

TABLE 5. Multiple Regressions of Respondent Sociodemographic Characteristics, Perceived Seriousness of Recent Water Scarcity, Perceived Likelihood of Severe Sustained Drought, and Perceived Vulnerability of Self and Area to Severe Drought on Acceptability of Mandatory Conservation to Address Water Scarcity Problems (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age	.166	–.082
Education (high school or less/ post high school)	.171	–.046
Gender	.111	–.136**
Length of Residence in Area	–.185*	–.025
Occupation (agriculture/other)	.008	–.041
Home Ownership (own or buying home/ other)	.180*	.056
Household Size	.220**	–.004
Household Income	–.087	–.084*
Perceived Seriousness of Recent Water Scarcity	.031	.084*
Perceived Likelihood of Severe Sustained Drought	–.054	.170**
Perceived Personal Vulnerability to Severe Drought	.041	.142**
Concern About Area Economic Effects of Severe Drought	.087	.108**
R^2	.163	.138

**P ≤ .05.
*P ≤ .10.

associated with being female, belief that future severe drought is likely, and perceived personal vulnerability to drought. However, the explanatory power of the independent variables was fairly low in both study areas.

Table 6 summarizes results with acceptability of water marketing as the dependent variable. In the Grand Valley there was a weak tendency for higher acceptance of marketing among younger respondents and those concerned about area economic effects of severe drought. In Kern County acceptance of marketing was somewhat greater among those with higher incomes. However, in both study areas the overall explanatory power of the independent variables was very weak, indicating that variation in support for water marketing is generally independent of the sociodemographic characteristics or perceptual variables considered here.

Finally, Table 7 presents results of regressing the sociodemographic and perceptual variables on acceptance of legislated reallocations of water supplies from agricultural use to municipal/industrial uses. In both areas only a modest amount of variation in the dependent variable was explained by the independent variables. In the Grand Valley those who tended to support such mandated reallocations were generally older and reported shorter periods of residence in the area, lower levels of concern about area economic vulnerability to severe drought, and greater perceived personal vulnerability to severe drought. In Kern County, acceptance of legislated reallocations tended to be higher among those who were less educated, reported shorter periods of residence in the area, were in nonagricultural occupations, had lower household incomes, perceived recent water scarcity as less serious, and were less concerned about area economic vulnerability to severe drought.

TABLE 6. Multiple Regressions of Respondent Sociodemographic Characteristics, Perceived Seriousness of Recent Water Scarcity, Perceived Likelihood of Severe Sustained Drought, and Perceived Vulnerability of Self and Area to Severe Drought on Acceptability of Water Marketing to Addressing Water Scarcity Problems (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age	–.141	–.011
Education (high school or less/ post high school)	–.096	.051
Gender	.222	.012
Length of Residence in Area	.083	.018
Occupation (agriculture/other)	–.005	.074
Home Ownership (own or buying home/ other)	.010	.001
Household Size	.107	.064
Household Income	–.018	.139**
Perceived Seriousness of Recent Water Scarcity	–.080	–.025
Perceived Likelihood of Severe Sustained Drought	.022	–.019
Perceived Personal Vulnerability to Severe Drought	.105	.012
Concern About Area Economic Effects of Severe Drought	–.132	.046
R^2	.077	.045

**P ≤ .05.
*P ≤ .10.

TABLE 7. Multiple Regressions of Respondent Sociodemographic Characteristics, Perceived Seriousness of Recent Water Scarcity, Perceived Likelihood of Severe Sustained Drought, and Perceived Vulnerability of Self and Area to Severe Drought on Acceptability of Legislated Reallocations From Agriculture to Municipal/ Industrial Uses to Address Water Scarcity Problems (standardized regression coefficients).

Independent Variables	Grand Valley	Kern County
Age	.163	–.061
Education (high school or less/ post high school)	–.062	–.127**
Gender	–.078	.025
Length of Residence in Area	–.269**	–.124**
Occupation (agriculture/other)	–.127	–.148**
Home Ownership (own or buying home/ other)	–.055	.078*
Household Size	.093	–.025
Household Income	–.080	–.117**
Perceived Seriousness of Recent Water Scarcity	–.023	–.105**
Perceived Likelihood of Severe Sustained Drought	–.015	.093**
Perceived Personal Vulnerability to Severe Drought	.162	.028
Concern About Area Economic Effects of Severe Drought	–.250**	–.142**
R^2	.151	.125

**P ≤ .05.
*P ≤ .10.

DISCUSSION

The results obtained from the comparative case study analyses reported here suggest several relevant conclusions. First, differential response patterns obtained from these two very distinct study areas reinforce the observation that efforts to assess water scarcity impacts need to focus attention on specific water user communities. Although there were some interesting response similarities across the study areas, the distinctions in their drought vulnerability and in the responses of residents to both recent drought experiences and a hypothetical severe sustained drought indicate that efforts to assess social impacts of severe drought must focus specifically at the level of individual water user communities. Substantial differences in both water resource conditions and the social/economic/political context of potentially impacted areas imply a potentially broad range of variability in the type and extent of impacts that might ensue from a severe sustained drought.

In addition, relationships between measures of drought perception, perceived vulnerability and acceptability of water management practices, and various sociodemographic and attitudinal characteristics of.survey respondents highlight the potential for differential drought response across water user niches. In these study areas, it is obvious that the niche occupied by persons engaged directly in agricultural enterprise is highly vulnerable to the effects of a severe sustained drought. At the same time, it is important to recognize that other segments of these communities are also extremely vulnerable to the effects of a severe sustained drought, even if they do not perceive that vulnerability. The absence of experience with drought conditions that even approach the level of severity envisioned under a severe sustained drought scenario makes it extremely difficult for residents of these communities to provide a realistic assessment of either their vulnerability or their probable responses to such conditions. Although serious effects might be felt earliest and most sharply in some water user niches such as the agricultural segment of the population, such effects would undoubtedly extend to affect a much broader range of community segments as the effects of drought extended beyond the 5-6 year time frame often associated with a severe but more "normal" drought to a period of 10, 15, or 20 years or more.

More generally, the results suggest that severe sustained drought has considerable potential for causing disruptive social consequences in both the Grand Valley and Kern County and, by extension, in other water user communities throughout the Colorado River Basin. At first glance, this conclusion may appear inconsistent with some of the survey results since respondents in both areas reported only minimal consequences of recent drought. Despite the relative severity of the 1986-1992 regional drought, water storage capabilities (surface water supplies in western Colorado and ground water supplies in Kern County) allowed both areas to avoid broad-ranging social and economic dislocations.

Nevertheless, highly disruptive impacts would be almost inevitable under the types of severe sustained drought conditions that were a focus of the broader project from which this research is drawn. Under such circumstances it is difficult to envision a scenario that would not include widespread economic dislocations across virtually all economic sectors. Such effects would likely contribute to significant shifts in demographic patterns, initially in the form of reduced levels of population growth and, eventually, in at least some level of outmigration as economically displaced persons moved elsewhere. There would also inevitably be substantial lifestyle shifts due both to income reductions and an inability to pursue many water-dependent activities such as landscaping, gardening, and some recreational activities. All of these effects would in turn have consequences for the levels of satisfaction and subjective sense of well-being experienced by members of affected communities, and for the type and extent of social and political conflicts that would arise in response to competition for increasingly scarce water resources.

Although it seems self-evident that severe sustained drought would cause major social disruptions, the evidence generated by this research provides relatively little reason for optimism about the capacity of these or other water user communities to respond effectively. Indeed, the ability of these communities to sustain more or less normal social and economic functioning during their recent experiences with water scarcity may actually work to the detriment of local response capabilities in the event of a severe sustained drought, for many people now think that it is possible to maintain "business as usual" rather than adopting more radical shifts in water resource management practices.

Residents of both areas are generally in agreement that there is a substantial likelihood of severe sustained drought in their areas within the next 20-25 years. They also express high levels of concern about the economic vulnerability of their communities to drought, although concern about personal financial vulnerability is somewhat lower. However, perceptions of vulnerability appear not to translate into support for water management practices and priorities that would run counter to "business as usual." Although there was a surprisingly high level of support in both areas for growth limitations or a construction moratorium to address water scarcity, there was substantial opposition to mandatory water conservation programs, and little support (especially in Colorado) for transfers of water from low- to high-population areas. Respondents from both areas expressed considerable opposition to water marketing and legislated reallocations of water from agricultural to municipal/industrial uses. They also assigned high priority to maintaining water availability for existing residential, agricultural, and industrial uses. Thus, any future efforts to implement some of the more "radical" water management strategies that would significantly reduce water allocations to some water communities or some types of users would likely generate considerable public outcry. Moreover, it is important to note that none of the management strategies addressed in the survey generated a consensus of opinion among local residents. The diversity of opinion about water management alternatives and the presence of some significant associations between acceptance of several of these alternatives and various respondent attributes such as education, length of residence, and income suggests a potential for conflicts to emerge between residents who support such approaches and those who are opposed.

Obviously, any attempts to project the impacts of water scarcity conditions as extreme as those envisioned under severe sustained drought are limited by the inherently hypothetical nature of such circumstances. Although hydrological models suggest that long-term extreme drought has occurred in the Southwest in the distant past, such events are beyond the scope of historically recorded experience in the study areas or any other part of North America. As a result, residents and water institutions have no base of relevant experience upon which to build response capabilities in the event of such a drought. Indeed, past experiences have largely reinforced the belief that social and economic conditions can be maintained at essentially normal levels for the duration of more or less "normal" short-term droughts, and at near-normal levels even when drought conditions persist for several years, as in the case of the 1986-1992 drought affecting the western United States. To some extent, the observation that support for more drastic water management alternatives tends to be higher among residents who perceive a higher likelihood of severe sustained drought and are more concerned about the consequences of such drought can be viewed as a hopeful sign that educational efforts regarding water communities' vulnerability to major disturbances in water availability could elicit more effective response capabilities. However, in the absence of information that could convincingly demonstrate that a drought will not be "normal" but instead be of unprecedented severity and duration, there is little likelihood that either residents or water institutions will be capable of effective or timely response. Implementation of more "radical" management responses will almost inevitably occur too late, when emergency conditions already exist. Unfortunately, unless this scenario of inadequate and delayed response can be changed, the potential for severe sustained drought to cause major social and economic dislocations is extraordinarily high.

APPENDIX 1.
SUMMARY OF SELECTED CHARACTERISTICS OF SURVEY RESPONDENTS

Percentages may not total to 100 percent due to rounding error

	Grand Valley (percent)	Kern County (percent)
Age		
Under 30	10.7	4.3
30 to 39	26.5	18.0
40 to 49	24.3	24.2
50 to 59	16.3	19.6
60 to 69	12.0	17.2
70 or older	10.2	16.7
Education		
Less than High School Diploma	9.8	13.8
High School	25.2	19.4
Some College/Post High School	37.1	35.5
College Degree	19.6	21.7
Graduate Degree	8.4	9.7
Gender		
Male	55.6	75.8
Female	44.4	24.2
Length of Residence in Area		
Under 5 Years	14.9	7.4
5 to 10 Years	9.8	8.8
11 to 20 Years	24.6	12.4
Over 20 Years	50.7	71.4
Home Ownership		
Own or Buying Home	83.9	90.4
Renting or Other	16.1	9.6
Household Size		
One	16.3	12.0
Two	29.1	40.3
Three	17.0	16.7
Four	23.4	18.2
Five or More	14.1	12.8
Household Income		
Under $10,000	3.7	7.8
$10,000 to $19,999	18.5	10.4
$20,000 to $29,999	29.6	12.1
$30,000 to $39,999	19.3	12.3
$40,000 to $49,999	11.9	13.0
$50,000 to $59,999	2.2	10.5
$60,000 to $69,999	6.7	7.3
$70,000 or More	8.1	26.8

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ASSESSING ENVIRONMENTAL EFFECTS OF SEVERE SUSTAINED DROUGHT[1]

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ABSTRACT: Evaluation criteria for reservoir and stream resources were developed to provide decision makers with feedback on environmental consequences of water allocation decisions under conditions of severe sustained drought within the Colorado River Basin by using the AZCOL gaming simulation model. Seven categories of flow dependent resources were identified which highlight resource states associated with reservoirs or river reaches within the AZCOL model. AZCOL directly simulates impact of water management decisions on five resource categories: threatened, endangered or sensitive fish; native nonlisted fish; wetland and riparian elements; national or state wildlife refuges; and hatcheries or other flow dependent facilities. Two additional categories – cold and warm water sport fish – are not modeled explicitly but are incorporated in the evaluation of monetary benefits from recreation on Colorado River waters. Each resource category was characterized at each time step in the simulation according to one of four environmental states: stable, threatened, endangered, or extirpated. Changes in resource states were modeled by time and flow-dependent decision criteria tied to either reservoir level or stream flows within the AZCOL model structure. Gaming results using the AZCOL model indicate environmental impacts would be substantial and that water allocation decisions directly impacted environmental resource states.
(KEY TERMS: aquatic ecosystems; modeling; water management; severe sustained drought; impact assessment.)

INTRODUCTION

This paper describes the development and application of flow-dependent environmental resource impacts due to water allocation decisions under simulated conditions of severe sustained drought within the Colorado River Basin. This effort was undertaken as an integral part of a broader multidisciplinary study to assess the hydrologic, economic, social, and environmental implications of water management decisions while coping with severe sustained drought in the southwestern United States (i.e., this volume). In particular, this specific effort focused on the development of flow-dependent environmental impact indicators that would be suitable for incorporation into the gaming simulation model of the study (see Lord *et al.*, 1995). The gaming simulation model (AZCOL) was used to describe and evaluate three different collective choice rule states for water allocation strategies within the Colorado River System under conditions of severe sustained drought (see Lord *et al.*, 1995).

One of the difficult challenges in developing flow-dependent environmental impact rules for use in the gaming model is related to the spatial and temporal scales over which these impacts may occur throughout the Colorado River Basin. Furthermore, the diversity and interrelationships between ecological components which are affected by flow-dependent changes, range across scales from watersheds down to interactions at the organism, population, and community level in both terrestrial and aquatic systems. For example, a compilation of the fisheries resources found in the Upper Colorado River Basin by Tyus *et al.* (1982) found that river segments contained 12 families represented by over 50 species. In addition, over 40 species were found to inhabit major reservoirs which were greater than 1,200 hectares in size. In a similar effort conducted on the fisheries resources within the Lower Colorado River, Minkley (1979) found over 40 fish species. This work found that of the 40 species reported from the Lower Colorado, 20 species are considered to represent the current ichthyofauna and typically five to six species are found concurrently at a given location. The number and particular species assemblage found at a site

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however, was found to be highly dependent on the localized macro- and micro-habitat conditions, even within a particular river reach.

The fish assemblages in Colorado River Basin rivers and reservoirs also contain both native listed and nonlisted species as well as a variety of important game species valued for their recreation potential. The life history requirements for spawning, egg incubation, rearing, adult holding, and overwintering habitats vary dramatically for individual species as do the flow-dependent critical conditions related to temperature, dissolved oxygen, and other water quality requirements. For example, spawning requirements in terms of temporal flow release patterns and water temperature regimes, can be narrowly focused over a few weeks to several months during either the spring, summer, or fall period depending on the species considered. Incubation requirements and length of time can also vary from as little as a week for some native species to as long as several months for some of the introduced salmonid species. Evaluations of the flow-dependent responses for the various life stages for many of the species are also largely unknown. In addition, many of the co-occurring species represent competitors or predators which can be either favored or inhibited due to the timing, magnitude, and duration of flow-dependent changes associated with severe sustained drought or resulting water management decisions for reservoir release rates. Many of the responses reported in the literature are at best inferential from limited studies in systems with much reduced species richness or from limited laboratory studies.

The rigorous evaluation of flow-dependent responses for the complexity of fish assemblages in the Upper and Lower Colorado River basins would require site-specific data on reservoir or river channel morphology, macro/micro-habitat availability and quality as a function of flow, and would necessarily require both temperature and water quality assessments. An evaluation of these physical and chemical changes at site-specific locations would also require the availability of flow-dependent responses for each target species and life stages. This level of comprehensive and systematic site-specific information, as well as species and life stage response information, is lacking for much of the reservoir and river reaches and species affected by flow management decisions evaluated during this study.

Given these factors, and in order to meet the objectives of this project, a broader view of component environmental effects for key elements of the flow-dependent resources within the basin was adopted. However, it was still desirable to provide some reach level specificity for environmental components for integration with the gaming simulation model. To this end, the structure of the gaming simulation model in terms of representing existing major storage facilities and river reaches which would be affected by alternative storage and release patterns were characterized in terms of seven broad resource categories. These resource categories were assigned one of four resource status codes which indicate the current environmental health or state of the resource. Decision rules which govern the change in resource status codes were then developed to reflect changes associated with either reservoir states or flow regimes within river reaches below the various storage facilities. This was accomplished by indexing the resource states to a percentage of the long term annual discharge based on research which associates health of the aquatic resources as a function of the annual flow statistics. A similar approach was also taken to categorize the other nonfisheries flow-dependent resources within the basin as noted below.

DELINEATION OF RESOURCE CATEGORIES

At the broadest level, from a physical, chemical, and biological perspective, the resource categories were broken down by either river or reservoir elements. This initial division parallels the current structure of the AZCOL model (see Lord *et al.*, 1995) which simulates reservoir conditions in terms of reservoir storage and river conditions in terms of inflow or release rates. The biological requirements for many fish species are also naturally divided along lentic versus lotic environments in terms of life history needs or attributes (Marshall, 1975). The principal reservoir and river reaches in which resource categories were defined are listed in Table 1. Lord *et al.* (1995) provides a complete description of the AZCOL model structure, function and application as part of the broader research study.

For both the reservoir and river elements, the fisheries were divided into four conceptual categories as: threatened, endangered, or sensitive (TES); native nonlisted (NNL); cold water sport (CWS); and warm water sport (WWS). The threatened, endangered, or sensitive category (TES) is intended to represent both the reservoir and river fish species which have either threatened or endangered status under the Endangered Species Act (ESA), Category 1 or 2 designations under the ESA, or listed on the respective State lists as species of special concern. It should be recognized that this category represents a wide array of species with very different life history requirements and flow-dependent response patterns which are conceptually accounted for in the decision rules governing their status as described below.

TABLE 1. Principal Reservoirs and River Reaches in Which Flow-Dependent Resource Categories Were Delineated for Use in the AZCOL Model.

State	Reservoir/River Reach
Arizona	Colorado River Below Lake Mead Lake Mead Lake Powell Lake Havasu
California	Colorado River Below Lake Mead Lake Mead Lake Havasu
Colorado	Yampa and White Rivers Below Their Confluence Gunnision River Below Curecante Recreation Area Colorado River Above Lake Powell Curecante Recreation Area Reservoirs
New Mexico	San Juan River Below Navajo Reservoir Navajo Reservoir
Nevada	Lake Mead
Utah	Green River Below Flaming Gorge Colorado River Above Lake Powell Flaming Gorge Reservoir Lake Powell
Wyoming	Green River Below Fontenelle Flaming Gorge Reservoir Fontenelle Reservoir

The native nonlisted species category (NNL) is intended to represent those components of both reservoir and river fish assemblages not covered by TES, CWS, or WWS categories but which represent important components of the ichthyofauna for a properly functioning aquatic ecosystem. This category of species is often represented by important forage base species for fish in the TES, CWS, and WWS categories. The cold and warm water sport fish categories (CWS and WWS) represent a distinction between those species within either reservoirs or river reaches which partition spatially in these habitats based on thermal requirements. All of the existing reservoirs evaluated in this study support both important cold and warm water sport fisheries such as trout versus bass, bluegill, or catfish. Similarly, river reaches below existing reservoir facilities show a longitudinal distribution between cold water and warm water sport fisheries as one moves downstream from tail waters of the reservoirs. In all cases, significant overlap between cold and warm water species exists over some reaches of the rivers which would be anticipated to be impacted by release patterns associated with either natural or man induced changes in releases from the reservoirs during severe sustained drought conditions. In formulating the AZCOL structure, the categories of cold water sport fish (CWS) and warm water sport fish (WWS) were not modeled explicitly, but were incorporated in the evaluation of monetary benefits from recreation on the Colorado river waters (see Lord *et al.*, 1995).

In addition to the fisheries resources within reservoir and river reaches, flow-dependent environmental categories for wetland and riparian elements (WAR), National or State Wildlife Refuges (NWR), and hatcheries or other flow-dependent facilities (FAC) were defined. For the purposes of this study it was assumed that all reservoir and river reaches would have significant wetland and riparian systems which would be affected by severe sustained drought. National or State Wildlife Refuges (NWR) and FAC categories were identified for particular reservoirs and river reaches based on interviews with state and federal resource managers who indicated that flow timing, magnitude, and duration effects associated with severe sustained drought would result in some form of a significant negative impact.

DEFINITION OF ENVIRONMENTAL RESOURCE STATES

In order to provide the decision makers for water allocations an indication of the current status of the resource categories for reservoirs and river reaches during the gaming simulations using the AZCOL model, four resource status codes were developed for association with each resource category. These resource states were defined as extirpated (EX), endangered (EN), threatened (TH), and stable (ST). The extirpated status code (EX) is intended to indicate the loss of that resource category due to impacts associated with the preceding flow or reservoir levels during the simulations. The distinction was made between extirpated and extinct, where the latter would indicate an irreversible loss of that resource which was assumed for this study not ever to occur for any of the categories. The endangered status code (EN) represents conditions for a particular resource which is in imminent danger of being lost if preceding flow or reservoir levels continue into the future. The threatened status code (TH) indicates that a particular resource category is presently in jeopardy and that its continued "survival" is questionable if current conditions do not improve. The stable status code (ST) indicates that the resource category is either experiencing stable conditions favorable to its continued survival or that populations are expanding.

INITIAL RESOURCE STATES FOR CRITICAL SYSTEM ELEMENTS

The initial resource category states at the start of all gaming exercises for AZCOL were determined by a consideration of the particular resource category (e.g., TES versus WWS), published literature, and discussions with federal and state resource managers familiar with a particular reservoir or river reach. It was assumed that all existing TES category resources would have an initial EN status given the implicit designations under the ESA or state protection lists. During gaming exercises, only the TES and WAR categories were provided to the participants unless specific information on other resource categories were requested. The player representing the Secretary of the Interior however, was provided output for all resource categories (see Lord *et al.,* 1995).

DECISION RULES FOR GOVERNING CHANGES IN RESOURCE STATES

As noted above, one of the most difficult challenges in implementing the impact assessments for the environmental resource categories was the lack of fundamental life history requirements and site-specific information upon which to develop flow-dependent response criteria. However, study results based on basinwide variables and annual flow relationships reported in the literature provides a rational framework for the development of decision rules to govern status changes as a function of both reservoir storage and river flows (e.g., Coutant, 1987; Fausch *et al.,* 1988; Schertzer and Sawchuk, 1990).

At present, over 75 models or methods have been used throughout the United States and Canada for the assessment of minimum instream flows or impacts associated with altered stream flow regimes on the aquatic environment (EPRI, 1986; CDM, 1986; Reiser *et al.,* 1989). A vast majority of these approaches, however, require differing amounts of site-specific cross section information or hydraulic modeling and the availability of species and life stage specific life history information such as depth and velocity preference and therefore were not suitable for consideration in this study. Of the remaining techniques which are based on some level of annual flow statistics, the Tennant Method (Tennant, 1976) probably represents the most defensible, reliable, and accurate approach (CDM, 1986). The Tennant Method is based on the analysis of hundreds of flow regimes in rivers from 21 different states and over 17 years of stream observations and professional judgment concerning the adequacy of various discharges to meet the needs of aquatic resources.

In the Tennant method, stream conditions are ranked from optimal to severely degraded as a function of the percent of mean annual flow which occurs during specific time periods of the year. The percent of mean annual flow associated with stream conditions between optimal and severely degraded based on Tennant's original work are shown in Table 2. In this study, for river based fisheries resource categories, these original ranges were modified to reflect conditions indicated by the four resource category states described in the previous section. Modifications were also made in order to facilitate computer coding and integration with the AZCOL model for use in the gaming simulation exercises as indicated in Table 2.

TABLE 2. River Resource State Classifications as a Function of the Percent of Mean Annual Flow Based on Tennant (1976) and Adopted Criteria for River and Reservoir States Used in the AZCOL Simulation Model.

Resource State	Percent of Mean Annual Flow
Tennant Resource Classifications	
Optimal	60-100
Outstanding	40-60
Excellent	30-50
Good	20-40
Fair or Degrading	10-30
Poor or Minimum	10
Severe Degradation	0-10
AZCOL Model Resource Classifications	
Rivers	
Optimal (SS1)	50-100
Good (SS2)	20-50
Poor/Fair (SS3)	5-20
Degraded (SS4)	0-5
Reservoirs	
Optimal (RS1)	50-100*
Good (RS2)	25-50
Poor/Fair (RS3)	Dead Pool-25
Degraded (RS4)	Empty

*Reservoir states are a percent of maximum storage capacity.

First, the flow patterns within a specific river reach during the time interval chosen for the simulation (i.e., five years) were categorized into one of four possible conditions based on the highest percentage of time river flows were maintained in the fixed percentages of the long-term average flow conditions as indicated in Table 2. These four river conditions correspond roughly to the Excellent to Optimal Range, the Good Range, Poor to Fair Range, and Severely Degrading Ranges from Tennant. Finally, a decision rule matrix was developed for defining the resource category state for each of the fisheries related resources (i.e., TES, NNL, CWS, and WWS) based on the resource category state at the beginning of the simulation period and the classification of the river state based on Table 2 at the end of the simulation time step (i.e., five years). Time-dependent impacts as well as recovery effects in the fisheries resource category states were also incorporated in the decision matrix based on general life history strategies. For example, an endangered status (EN) for warm water species (WWS) could only improve to threatened (TN) during the five-year simulation period given a river state categorization in the Optimal Range to account for population recovery times. But at the same time, WWS categorized as EX could improve two levels to TH in that same five-year period given the generally greater population response times for these types of species. Similarly, any simulation period in which flows were categorized as severely degraded within a river reach would result in an extirpated status (EX) for the fisheries resource categories of CWS, WWS, and TES, regardless of the initial resource state at the start of the simulation for that period. The NNL resource category, however, could retain an EN status under degraded conditions if the initial states were either ST or TH given the ability of many suckers and minnows represented by this group of species to exist under extremely low flow levels for protracted periods of time. This differential response pattern for NNL was also assumed given that the degraded category in Table 2 covers a range of flows between 0 and 10 percent of mean annual flow, not necessarily that no flow conditions existed over the entire simulation period. If, however, the simulation showed no flow within a river reach over the entire five-year simulation period, any fisheries resources were set to EX within the model. The embedded time lag for improving conditions and subsequent changes in resource states is intended to reflect the commonly observed time lags for recoveries of fish populations due to density dependent controls on spawning and recruitment and resulting year class strength.

Analytical approaches similar to Tennant (1976) for wetland, riparian, refuges and other flow-dependent facilities are not well developed in the literature and professional judgment was used to formulate similar criteria for these categories based on the framework of Tennant (1976). Federal and State resource managers were interviewed, particularly in regards to the refuge and facilities categories, in order to derive the decision matrices for these elements. An example of the finalized decision matrices for river based environmental resource categories are provided in Table 3. A complete listing for all river reaches used in the AZCOL model can be found in Hardy (1995).

A parallel process was also utilized for the specification of reservoir states based on the percent of time that the reservoir capacity remained within a fixed percentage of maximum reservoir storage capacity. The four reservoir states used for the AZCOL modeling exercises are provided in Table 2 and are intended to "mimic" the range between Optimal and Severely Degraded categories of Tennant (1976) for river based resources. No specific studies or analytical approaches for reservoir level impacts could be found during the literature searches and these intervals were based on inference from literature sources, professional judgment, life history considerations of fish species and discussions with both Federal and State resource managers. An example of the finalized decision matrices for reservoir based environmental resource categories is provided in Table 4. Decision criteria for the wetland and riparian elements were inferred from work by Tennant (1976); Harris *et al.* (1987); Kondolf *et al.* (1987); Stromberg and Patten (1990); Hill *et al.* (1991); and Smith *et al.* (1991). Decision rules for refuges and facilities categories were primarily determined from discussions with State and Federal resource managers. As indicated previously, a complete listing of all decision matrices utilized in the AZCOL gaming simulation model can be found in Hardy (1995).

EXAMPLE OF GAMING SIMULATION RESULTS

The AZCOL gaming simulation model was utilized to examine water allocation strategies adopted by players under three different gaming scenarios. The simulation games utilized the project hydrology shown in Figure 1 under three different institutional water allocation strategies which are described in detail in Lord *et al.* (1995). Table 5 provides an example of the changes in selected resource categories at river and reservoir sites over a 30-year period for one of the three severe sustained drought scenarios using the AZCOL gaming simulation model. It is apparent that TES resource categories were extirpated from the Green River below Flaming Gorge as well as within Flaming Gorge. Similar problems were also encountered for TES categories in Navajo Reservoir and Lake Powell. The wetland and riparian resource categories (WAR) were also significantly impacted at both Curecanti and below Flaming Gorge, and to a lesser extent at Fontenelle Reservoir. Knowledge of these changes to resource states under each of the

TABLE 3. Example of Decision Rule Matrices Used to Define Environmental Resource States for Specific River Reaches in the AZCOL Model (see Table 2 for reservoir and river status codes).

Location:	Green River Below Fontenelle
Given: NNL = ST:	IF SS1 then ST; IF SS2 then ST; IF SS3 then TH; IF SS4 then EN
Given: NNL = TH:	IF SS1 then ST; IF SS2 then ST; IF SS3 then TH; IF SS4 then EN
Given: NNL = EN:	IF SS1 then ST; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: NNL = EX:	IF SS1 then TH; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: CWS = ST:	IF SS1 then ST; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: CWS = TH:	IF SS1 then ST; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: CWS = EN:	IF SS1 then TH; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: CWS = EX:	IF SS1 then TH; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: WWS = ST:	IF SS1 then ST; IF SS2 then ST; IF SS3 then TH; IF SS4 then EX
Given: WWS = TH:	IF SS1 then ST; IF SS2 then ST; IF SS3 then TH; IF SS4 then EX
Given: WWS = EN:	IF SS1 then TH; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: WWS = EX:	IF SS1 then TH; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: NWR = ST:	IF SS1 then ST; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: NWR = TH:	IF SS1 then ST; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: NWR = EN:	IF SS1 then TH; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: NWR = EX:	IF SS1 then TH; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: FAC = ST:	IF SS1 then ST; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: FAC = TH:	IF SS1 then ST; IF SS2 then TH; IF SS3 then EN; IF SS4 then EX
Given: FAC = EN:	IF SS1 then TH; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: FAC = EX:	IF SS1 then TH; IF SS2 then EN; IF SS3 then EN; IF SS4 then EX
Given: WAR = ST:	IF SS1 then ST; IF SS2 then ST; IF SS3 then TH; IF SS4 then TH
Given: WAR = TH:	IF SS1 then ST; IF SS2 then TH; IF SS3 then TH; IF SS4 then EN
Given: WAR = EN:	IF SS1 then TH; IF SS2 then TH; IF SS3 then EN; IF SS4 then EN

TABLE 4. Example of Decision Rule Matrices Used to Define Environmental Resource States for Specific Reservoirs in the AZCOL Model (see Table 2 for reservoir and river status codes).

Location:	Fontenelle Reservoir
Given: NNL = ST:	IF RS1 then ST; IF RS2 then ST; IF RS3 then TH; IF RS4 then EN
Given: NNL = TH:	IF RS1 then ST; IF RS2 then ST; IF RS3 then TH; IF RS4 then EN
Given: NNL = EN:	IF RS1 then ST; IF RS2 then TH; IF RS3 then EN; IF RS4 then EN
Given: CWS = ST:	IF RS1 then ST; IF RS2 then TH; IF RS3 then EN; IF RS4 then EX
Given: CWS = TH:	IF RS1 then ST; IF RS2 then TH; IF RS3 then EN; IF RS4 then EX
Given: CWS = EN:	IF RS1 then ST; IF RS2 then TH; IF RS3 then EN; IF RS4 then EX
Given: CWS = EX:	IF RS1 then TH; IF RS2 then TH; IF RS3 then EN; IF RS4 then EX
Given: WAR = ST:	IF RS1 then ST; IF RS2 then ST; IF RS3 then ST; IF RS4 then TH
Given: WAR = TH:	IF RS1 then ST; IF RS2 then ST; IF RS3 then ST; IF RS4 then TH
Given: WAR = EN:	IF RS1 then ST; IF RS2 then ST; IF RS3 then ST; IF RS4 then TH
Given: HAT = ST:	IF RS1 then ST; IF RS2 then ST; IF RS3 then TH; IF RS4 then EX
Given: HAT = TH:	IF RS1 then ST; IF RS2 then ST; IF RS3 then EN; IF RS4 then EX
Given: HAT = EN:	IF RS1 then ST; IF RS2 then ST; IF RS3 then EN; IF RS4 then EX
Given: HAT = EX:	IF RS1 then ST; IF RS2 then ST; IF RS3 then EN; IF RS4 then EX

three gaming scenarios, allowed players to consider alternative management decisions which would potentially protect these resources. These results are also important in terms of using the AZCOL model to explore alternative management decisions where reduction in severe degradation of TES category resources at one site may be considered in terms of accepting lesser degradation of alternative resources categories at another site given alternative water management decisions.

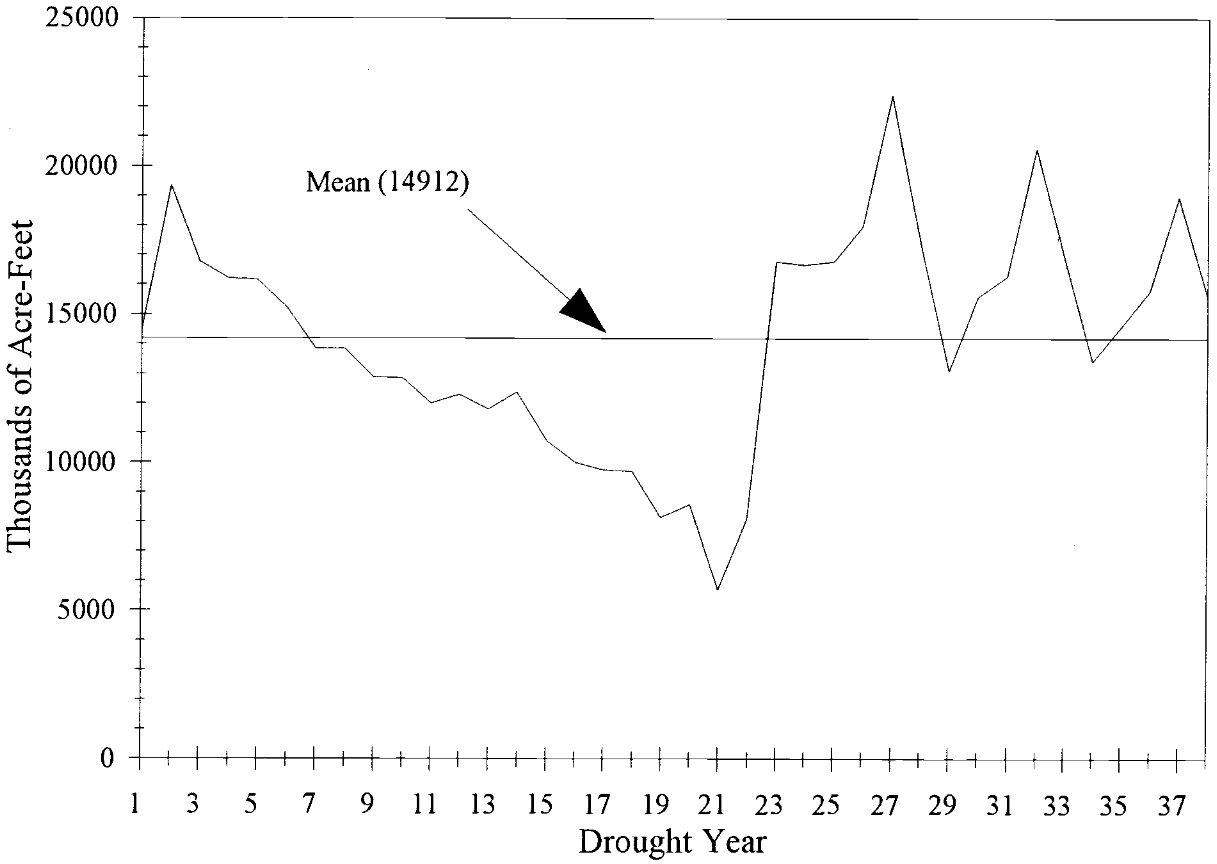

Figure 1. Severe Sustained Drought Scenario Utilized in the AZCOL Gaming Simulations (after Lord *et al.*, 1995).

TABLE 5. Example of Threatened and Endangered Fish Species (TES) and Wetland and Riparian (WAR) Resource Categories Changes by Reservoir and River Reaches Over a 30-Year Severe Sustained Drought Gaming Scenario Using the AZCOL Model.

Resource Categories/States*	Year of Drought																													
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
TES Below Flaming Gorge	2	2	2	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
TES Below Green and Colorado Confluence	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
TES Below Lake Mead	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
TES Below Navajo Reservoir	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
TES in Flaming Gorge	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2
TES in Lake Mead	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
TES in Navajo Reservoir	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	2	2
TES in Yampa River	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
TES in Lake Powell	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
WAR Below Curecanti	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
WAR Below Flaming Gorge	4	4	4	3	3	3	3	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
WAR Below Fontenelle Reservoir	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
WAR Below Green and Colorado Confluence	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
WAR Below Lake Mead	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
WAR Below Navajo Reservoir	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
WAR in Fontenelle Reservoir	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	4	4
WAR in Yampa River	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

*Resource Category States: Stable = 4, Threatened = 3, Endangered = 2, Extirpated = 1.

Table 6 provides a summary of the environmental impacts of severe sustained drought for each of the three gaming simulations using the AZCOL model based on the drought hydrology provided in Figure 1 (after Lord *et al.*, 1995). Deteriorations and improvements indicate the number of times that a resource state either showed an improvement or degradation during succeeding time steps during the gaming simulation. The inclusion of "worst case" under impacts on threatened and endangered species represents the number of times extirpations occurred for this resource category. A positive value for the "net losses" category represents environmental deterioration, while a negative score indicates an overall improvement. It should be noted that the large number of improvements reflected in these results is due to the characteristic of the drought hydrology used during the AZCOL simulations (Figure 1) which shows a recovery of flows to predrought conditions over the last half of the simulation. In all cases, general environmental recovery occurred during the last 19 year period associated with improved flow characteristics. During each of the three simulation games using AZCOL, the player representing the Secretary of the Interior invoked the Endangered Species Act to modify reservoir release rates to protect these resources. In the case of the first simulation game, this was initiated in year 5, while in the remaining two simulation games, flow alterations were invoked for environmental protection during year 18. In general, there was a net improvement in conditions for the endangered and threatened species in each of the three simulation games. This can be seen from the results in Table 6 which indicate a reduction of worst case or extirpations. The results presented in Table 6 also highlight the issue of competing environmental consequences of water allocation decisions between resource categories. In each gaming scenario, water allocation decisions result in differential impacts or improvements between the various resource categories that reflect a wide array of water allocation strategies employed during the gaming exercise. This is often observed during impact assessments of proposed projects which alter flow regimes below reservoirs, where differential water release scenarios either favor or impact different resource categories. A more detailed treatment of the complete simulation results can be found in Lord *et al.* (1995).

TABLE 6. Example of Environmental Impacts of Severe Sustained Drought on Resource Categories Using Three Gaming Scenarios of the AZCOL Model (after Lord *et al.*, 1995).

Type of Impact	Game 1	Game 2	Game 3
Impacts to Threatened and Endangered Species			
Deteriorations	5	8	7
Improvements	13	11	10
Net Losses	-8	-3	-3
Number of Worst Cases	21	32	30
Impacts on Wetlands and Riparian Areas			
Deteriorations	4	4	4
Improvements	2	2	2
Net Losses	2	2	2
Impacts on Hatcheries/Flow-Dependent Facilities			
Deteriorations	18	7	18
Improvements	12	14	14
Net Losses	6	-7	-4
Impacts on Native and Non-listed Fish			
Deteriorations	19	22	13
Improvements	15	19	17
Net Losses	4	3	-4
Impacts on National Wildlife Refuges			
Deteriorations	16	14	17
Improvements	11	14	11
Net Losses	5	0	6

SUMMARY AND CONCLUSIONS

Broad based environmental resource categories for several fisheries types, wetland, riparian, refuges, and other flow dependent facilities were developed for both river and reservoir sites for use in the AZCOL model. Resource categories were placed into one of four states which ranged from extirpated to stable in order to reflect current conditions based on the previous flow regimes or reservoir storage conditions. A decision matrix which implicitly accounts for the predominant river flow or reservoir storage conditions during the previous simulation period, initial environmental resource category state, and time lag biological responses was developed based on studies which relate environmental health of these resource categories to a percentage of the long term annual flow or maximum reservoir storage. Integration of the decision matrix for the environmental resource categories for each reservoir and river reach into the AZCOL gaming simulation model provided the water allocation decision makers with feedback on management decisions in terms of the affected environmental resource categories. AZCOL gaming simulations demonstrated changes in resource states over a 38-year period that reflected an initial decline in environmental conditions during the first 19-year severe sustained drought followed by a recovery of the environmental resources during the last 19-year period when flows returned to more normal conditions. In all three AZCOL gaming exercises, water allocations decisions where to some degree predicated on the state of the environmental resources, in particular in light of the status of the endangered and threatened species category. Water allocation strategies were also shown to cause a differential effect on the state of the various environmental resource categories that reflect the competing consequences of water allocation strategies often observed during real world applications.

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COMPETING WATER USES IN THE SOUTHWESTERN UNITED STATES: VALUING DROUGHT DAMAGES[1]

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ABSTRACT: Economic benefit functions of water resource use are estimated for all major offstream and instream uses of Colorado River water. Specific benefit estimates are developed for numerous agricultural regions, for municipal uses, and for cooling water in thermal energy generation. Economic benefits of hydropower generation are given, as are those for recreation on Colorado River reservoirs and on one free-flowing reach. Marginal and total benefit estimates for Colorado River water use are provided. The estimates presented here represent a synthesis of previous work, providing in total a comprehensive set of economic demand functions for competing uses of Colorado River water. Non-use values (e.g., benefits of preserving endangered species) are not estimated.
(KEY TERMS: water demand; drought; economic benefits; irrigation; municipal water demand; recreation; hydropower, salinity.)

INTRODUCTION

Water resources provide critical services to a wide range of consumptive and non-consumptive users in the southwestern United States. Water is consumptively used for irrigation of crops, and for municipal and industrial purposes in cities and towns, including cooling water for thermal electric generation. Instream flows (derived largely from storage in regional reservoirs) generate hydropower, provide unique habitat, and are required for a variety of recreational activities. While total benefits from use of all regional water resources might possibly be estimated, our purpose here is more modest. We are concerned primarily with estimation of damages (lost economic benefits) resulting from a range of marginal or incremental reductions in water availability, and also with examining water users' incremental adjustments to drought-induced water reductions.

We focus on those activities in the southwestern United States which typically utilize water from the Colorado River Basin, the dominant water supply for the region. Basin water can be delivered to a population of over 25 million across seven states, from Wyoming to California. Total consumptive use exceeds 10 million acre-feet (maf), with an additional 1.5 maf used in northern Mexico. Hydropower sufficient for the electricity needs of 4 million residential users is generated by water released from Basin reservoirs. The same reservoirs are also major recreational attractions, with approximately 17 million visitor days per year. Fishing and rafting on the mainstem and tributaries provide further benefits.

We value these sometimes competing uses of Basin water by developing economic benefit functions for the major uses. Economic benefits of consumptive use in agricultural, municipal, and energy sectors at a number of locations are first estimated. Many of these uses are affected by high concentrations of dissolved minerals (salinity) in Colorado River water which cause damages to water-using appliances in municipal uses, and reduce crop yields in irrigation uses. Damage estimates from a prior study by one of the authors (Booker and Young, 1991) are used to value these salinity damages. Economic benefit estimates for instream, non-consumptive uses (hydropower and recreation) are also developed. While instream flows provide general and critical habitat for a rich spectrum of Basin wildlife, no attempt is made to place an economic value on habitat for endangered or other species. Similarly, other non-use values are not treated.

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Specific approaches to measuring economic benefits for each use are developed here and applied to evaluate the foregone benefits (damages) during drought. The benefit estimates presented here are largely based on previously reported research. Our primary contribution is the synthesis of studies by numerous authors covering a variety of offstream and instream uses. The result is a complete set of economic benefit functions suitable for use in estimating economic damages of reduced water resource availability in the southwestern United States. All monetary values are given in 1992 dollars.

We identify only the direct economic damages from drought. Additional indirect damages will occur through reductions in regional purchases and employment resulting from drought. For example, shortages of irrigation water may result in a failure to produce an agricultural crop. The resulting income loss to the landowner is the direct economic damage of drought reported by this study. Lost wages to farm workers and lost income to regional businesses supplying (or purchasing from) irrigated farms are termed indirect or secondary economic impacts. While potentially significant to local and regional economies, indirect impacts to national economies are zero under conditions of full employment. Because regional links to the national economy are not identified here, only partial equilibrium analysis of direct economic impacts is possible [see Brookshire *et al.* (1993) for a discussion of indirect and general equilibrium impacts of regional water supply reductions].

DEVELOPING ECONOMIC DEMAND FUNCTIONS FOR CONSUMPTIVE USES

Consumptive uses include irrigated crop production, provision of household services such as showers and landscaping, and evaporative cooling in industrial processes such as electric power generation. Consumptive use of Colorado River water is assigned to one of three sectors: agricultural, municipal, or energy use. Within each sector a single methodology is followed in developing economic demand estimates for water use. Economic demand estimates for actual offstream diversions are developed by scaling each regional, sectoral demand estimate to depletion data originally developed for use in the U.S. Bureau of Reclamation (USBR) Colorado River Simulation Model (1991) and modified for this study.

Agricultural Demand Functions

Water demand functions which summarize the direct marginal economic benefits of utilizing irrigation water from the Colorado River are derived here from linear programming models of regional irrigated agricultural production. Several independent modeling efforts were utilized in developing the comprehensive set of benefit functions presented here. For consistency, all water use figures given in the original modeling efforts were converted to consumptive use figures, with benefit estimates updated to 1992 dollars using the GNP price deflator.

Linear programming models frequently require the use of ad hoc crop flexibility constraints to calibrate predicted crop acreage to observed crop acreage (as reported in state crop summary reports, for example). In several of the studies used here, lower bounds on crop acreage resulted in models giving unreasonably high predictions of damages from reductions in crop production caused by irrigation water shortages. Uncritical acceptance of such estimates would suggest unrealistically inelastic water demand functions, and hence unrealistically high marginal water values at large reductions from existing use levels. Because the underlying calibration constraints which cause this difficulty vary greatly between studies, an attempt was made to correct for this effect. First, an estimate of the average benefit of irrigation water use was developed to help identify artificially high damage estimates (e.g., greater than \$100/acre-foot (af) in Upper Basin uses). Because agricultural land values implicitly reflect the average value of water in irrigated crop production, average benefits of irrigation water use were estimated from state land values (U.S. Department of Agriculture, 1990) using average irrigation water requirements for each state (U.S. Department of Agriculture, 1992). A 4 percent discount rate was used to calculate annualized irrigated land values. Reported marginal water values (shadow prices) which exceeded the average estimated water value by more than 20 percent at greater than 50 percent of full water supply were then excluded from the benefit function estimates reported here.

After adjustments for the programming artifacts described above, water demand (marginal benefit) schedules were developed from the reported programming solutions for each region. For any particular region, this initial demand schedule frequently included marginal values estimated from several studies. From this initial schedule a single marginal benefit, or (inverse) demand function of the form

$$p(x) = p_0 \, (x/x_0)^{\alpha} \tag{1}$$

for $0 < x \le x_0$, was estimated by least squares regression. In Equation (1), x_0 is the maximum water delivery, p_0 is the willingness to pay for addition water at full delivery, and α is the inverse of the price elasticity of demand. The Cobb-Douglas form was chosen because it successfully fit most demand schedules constructed for this study; linear demand functions were particularly limited in capturing the nonlinearities in most schedules. The range of R^2 for the 11 estimated functions was 0.55 to 0.95; $R^2 \ge 0.8$ and 2 to 3 degrees of freedom were typical. The underlying demand schedules included meaningful marginal benefit values for use reductions to approximately 0.5 x_0. Use of the estimated demand functions for greater water use shortfalls would require extrapolating beyond any data available to this study.

Total benefit functions were also desired as a baseline from which to measure drought damages. Because the estimated (inverse) demand functions have little empirical content below 50 percent of full water delivery, however, simple integration of Equation (1) is inappropriate. Instead, the average water values described above were utilized to derive total benefit functions V(x) such that $V(x_0) = x_0\,\bar{v}$, where $\bar{v}$ is the average benefit (in \$/af) from irrigation water use calculated from irrigated land values. By maintaining that the estimated demand functions do not hold for low water use, the problem of nonconvergence of an inelastic Cobb-Douglas demand function is also avoided. Table 1 gives estimated total benefit functions, average water values, elasticities, and marginal water values at full delivery, for 11 agricultural regions covering agricultural users of basin water.

Because the studies on which Table 1 is based were published over a broad time span (1973 to 1988), there was concern that real changes in agricultural water values might have resulted from changes in farm income due to trends in output versus input prices, and technological change. Our data showed no evidence of real changes in marginal water values, however: adjusting marginal water values for changes in reported farm income (U.S. Department of Agriculture, 1984, 1991) did not decrease variances across studies.

Central and Southern Region. The region includes uses in portions of Colorado, New Mexico, and Utah. Studies by Booker and Young (1991) for the Grand Valley; Oamek (1990) for the mainstem of the upper Colorado, the Gunnison, and the Dolores; and Howe and Ahrens (1988) (similar regions to Oamek) were utilized in part to develop the water demand functions. Irrigation uses in the San Juan River Basin are also included. Demand estimates for the region by Oamek (1990) and Howe and Ahrens (1988) were used, together with estimates at three sub-regional elevations by Gollehon *et al.* (1981).

Northern Region. The region includes uses in Wyoming (mainstem of the Green River) and portions of Colorado and Utah. Tributary uses on the Yampa, White, Duchesne, Price, and San Rafael Rivers are included. Four previous studies are available from which to estimate the water demand functions. Marginal values are given by Anderson (1973) for the Uintah Basin in Utah; by Gollehon *et al.* (1981) for

TABLE 1. Estimated Agricultural Total Benefit Functions.*
Average water values, elasticities, and marginal water values at full delivery for each use (1992 dollars).

Agricultural Region	v_0 (\$/af)	β	Proportion of Non-Colorado River Water Used $x_n/(x_n + x_0)$	Average Water Benefit $\bar{v}$ (\$/af)	Marginal Value at Full Use p_0 (\$/af)	Price Elasticity of Demand**
Western Colorado	–16.3	–0.75	0.000	30.6	12.2	–0.57
Colorado Front Range	–10.8	–1.24	0.873		13.4	–0.45
Wyoming	–23.6	–0.53	0.000	14.2	12.5	–0.65
Utah	–23.6	–0.53	0.000	37.8	12.5	–0.65
New Mexico	–16.3	0.75	0.000	51.2	12.2	–0.57
San Juan-Chama Export	–16.3	–0.75	0.800		12.2	–0.57
Nevajo IIP	57.8	0.93	0.000	51.2	53.9	–14.77
CAP	46.0	0.59	0.725		27.1	–2.44
Colorado River Indian Tribe	32.9	0.44	0.000	36.3	14.5	–1.79
Yuma	83.2	0.24	0.100		20.0	–1.32
California	–29.5	–0.92	0.000	39.4	27.2	–0.52

*Use of parameters v_0, β, x_n, x_0, $\bar{v}$, and p_0 in the total benefit function is described in the text.

**If non-Colorado River supplies are available, this elasticity holds only at full water delivery.

Routt and Moffitt Counties in Colorado (Yampa and White Rivers) and Uintah and Duchesne Counties in Utah (Green and Duchesne Rivers); by Howe and Ahrens (1988) for the Yampa and White Rivers and the Green River above the Colorado; and by Oamek (1990) for this entire "Northern region" (his "PA 82"). Weighted averages (based on consumptive use) are used to aggregate sub-regional estimates of Howe and Ahrens (1988) and of Gollehon *et al.* (1981) to the regional level, while estimates from Anderson (1973) and Oamek (1990) are used directly.

Colorado Front Range. Irrigated production on Colorado's eastern plains makes use of transmountain water exports from the Colorado River Basin. Demand for agricultural water was estimated from a minor revision of the model of northern Colorado agricultural production presented in Michelsen (1989). Crop flexibility constraints were modified in order to allow estimates of damages from up to 50 percent reductions in water use.

California. Estimates from a programming model developed by Booker and Young (1991) are used as the basis for water demand functions for California users of Colorado River Basin water. This model focused on irrigated production in the Imperial Valley, the major user of Colorado River water in southern California.

Arizona. Water demand functions for three distinct users in Arizona (Yuma, Colorado River Indian Reservation, and Central Arizona) were derived from the farm-level programming results obtained by Peacock (unpublished manuscript, Dept. of Agricultural and Resource Economics, University of Arizona, 1993). Two representative farms in the Yuma region were modeled, one with field crops only and one with both field and vegetable crops. A third representative farm, growing mostly cotton, was modeled using the enterprise budget given in Wilson (1992).

Net benefit functions were derived from point estimates of benefits in each of the three models. A portfolio of the three farms which best matched county acreages (minimized the sum of squared deviations from estimated crop acreages) of cotton, wheat, alfalfa, and vegetables was then constructed. A programming model of water allocation within each region was developed to estimate regional benefits from water use. Effective markets within regions were assumed, allowing reallocations among the three farm types when diversions were less than 100 percent. The resulting regional net benefit point estimates were then re-estimated to give a continuous function representing regional benefits.

Municipal Demand Functions

Municipal demand estimates were derived for major southwestern cities, including Phoenix/Tucson, Denver/Front Range, Salt Lake City, Las Vegas, Albuquerque, and the Metropolitan Water District (MWD) service area in southern California. A single cross-sectional study of seasonal household water demand (Griffin and Chang, 1991) was used as the basis for deriving the set of unique but methodologically consistent benefit functions for each municipal region. The approach was based on the observation that the proportion of outdoor to indoor uses varies across regions as a result of climate differences and socioeconomic factors. Summer and winter elasticities of -0.41 and -0.30 reported by Griffin and Chang (1991) for their generalized Cobb-Douglas estimate were used. Following Howe (1982), these are converted to indoor and outdoor elasticity estimates of -0.30 and -0.58. For example, using this procedure with data on indoor and outdoor use in Phoenix and Tucson gives average annual elasticities of -0.43 and -0.39, respectively. These are similar to the range of average elasticities (-0.27 to -0.70) reported in several studies by Billings and Agthe (1980) and Martin and Kulakowski (1991) for Tucson, and Planning and Management Consultants (1986) for Phoenix, as well as the range reported in the numerous other studies on this topic. Municipal demand functions were then estimated using the *average* water prices and use levels for 1985. Table 2 summarizes marginal and total benefit function estimates for Basin municipal uses.

Thermal Energy Demand Functions

Water is used for cooling water in thermal electric generation throughout the Southwest. A single benefit function for cooling water at thermal electric power generating facilities was re-estimated from data on costs of alternative cooling technologies presented in Booker and Young (1991). Actual long-run benefits may tend to be overestimated using this approach, given the possible availability of local ground water for use in cooling. The avoided cost approach may underestimate short-run damages from water shortages, however, given the necessary capital investments for use of water conserving cooling technologies. The estimated benefit function for cooling water use is $V(x) = x_0\, v_0\, (x/x_0)^{\beta}$, where v_0 = \$222/af, $\beta = -.070$, and $0 < x \leq x_0$. The benefit function implies a marginal water value of \$155/af and price elasticity of demand equal to -0.59 at full delivery.

TABLE 2. Estimated Municipal Benefit Functions,* Elasticities,** and Marginal Water Values at Full Delivery for Each Use (1992 dollars).

Agricultural Region	v_0 (\$/af)	β	Proportion of Non-Colorado River Water Used $x_n/(x_n + x_0)$	Marginal Value at Full Use p_0 (\$/af)	Price Elasticity of Demand
Denver	–373	–1.22	0.602	455.1	–0.45
Central Utah Project	–369	–1.23	0.884	453.9	–0.45
Albuquerque	–298	–1.61	0.495	479.8	–0.38
Las Vegas	–318	–1.27	0.050	403.9	–0.44
Central Arizona	–277	–1.31	0.626	362.9	–0.43
MWD (South California)	–211	–1.63	0.608	343.9	–0.38

*Use of parameters v_0, β, x_n, x_0, and p_0 in the total benefit function is described in the text.

**Because non-Colorado River supplies are available, elasticities given are at full water delivery.

Consumptive Use Depletion Requests

Full economic demand functions for consumptive use of Colorado River water are found using the demand estimates presented above together with USBR (1991) depletion data. The USBR data set gives the legal entitlements for consumptive use and is used to define a "full" delivery depletion schedule for each Basin use. This is the only source for spatially disaggregated estimates of Basin depletions, and it is the starting point for the consumptive use inputs in the modeling of drought impacts by Harding *et al.* (1995), Booker (1995), Henderson and Lord (1995), and Sangoyomi and Harding (1995), all reported in this issue.

The actual depletion schedule used in these studies modifies the USBR schedule by holding agricultural depletions constant at 1992 levels and shifting the Central Arizona Project (CAP) schedule back six years (from 1992 to 1986) to reflect recent low deliveries. CAP deliveries in excess of 1,248 thousand acre-feet (kaf) per year (surplus deliveries) are not included because there is little evidence of demand for these deliveries (Wilson, 1992). The Las Vegas depletion schedule is allowed to increase with population, irrespective of Nevada's limited Colorado River Compact entitlement. The total adjusted increase in depletion schedules for the period 1992 to 2030 is approximately 10.5 percent (1,350 kaf). Synthetic fuel development accounts for 233 kaf of new depletions. The annual growth rate in depletions is less than 1 percent, in contrast to U.S. Bureau of the Census (1990) projections of population growth of 1.2, 1.8, and 0.9 percent annually from 1990 to 2010 for California, Arizona, and Colorado, respectively.

Derivation of Total Benefit Functions

Estimation of total (direct) economic benefit functions for consumptive uses requires scaling demand functions to the level (scheduled depletion x_0) of each use, treatment of alternative water supplies, and use of additional data where demand functions are not defined for very low use levels. If the (inverse) demand function given in Equation (1) holds for $0 < x \le x_0$ (and the price elasticity is not inelastic), then the total benefit V(x) of water use x is found directly by integration of Equation (1), giving

$$V(x) = x_0 \, v_0 \, (x/x_0)^{\beta} \tag{2}$$

where $v_0 = p_0 / (\alpha + 1)$ and $\beta = \alpha + 1$. Equation (2) is typically an oversimplification, however. First, most water users (particularly municipal and energy) have available an alternative water supply source (e.g., ground water). For simplicity, it is assumed that this alternative source is the inframarginal source and that a fixed amount is always utilized. Second, for agricultural water uses, Equation (2) holds only for $x/x_0 \ge 50$ percent of total requests because of limitations in the underlying data. In this case, additional data is needed to complete the integration.

Adjustment for Non-Colorado River Water. If a particular use has water available from a non-Colorado River source, then Equation (2) describes not the benefit from Colorado River use, but instead the benefit from all use. This is shown in Figure 1 where (a) shows the total benefit function V(x) from all sources; the solid line in Figure 1 is a total benefit function for Colorado River use alone, assuming that other supplies are inframarginal. It is desirable to set the total benefit $V_c(x')$ from use of Colorado River water x' to zero for $x' = 0$, as shown in Figure 1(b). Mathematically, the benefit $V_c(x')$ from use of Colorado River water x' is then given by

$$V_c(x') = (x_n + x_0)\, v_0 \{((x_n + x')/(x_n + x_0))^\beta - (x_n/(x_n + x_0))^\beta\} \tag{3}$$

where x_n is the consumptive use of non-Colorado River water which serves as the inframarginal supply and x_0 is the maximum use (the depletion schedule) for Colorado River water. Note that the total benefit from Colorado River use $V_c(x_0)$ is now implicit in Equation (3) and is given by $V(x_0 + x_n) - V(x_n)$. The demand for Colorado River water is more elastic than the demand from all sources and is non-constant.

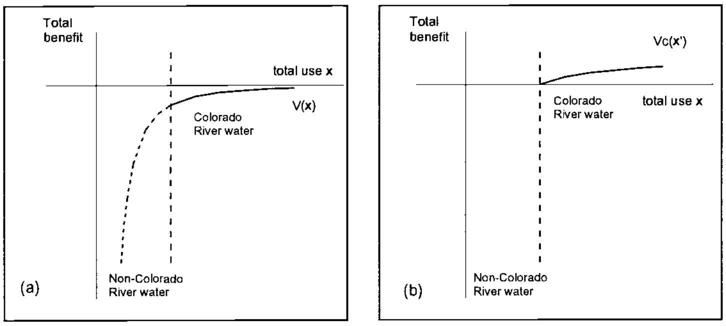

Figure 1. Benefit Function V(x) When Demand is Inelastic for Consumptive Use x from All Sources (a). In (b), $V_c(x')$ is the Benefit Function for Colorado Water Only.

Use of Average Water Use Benefits. It is useful to have an estimate of the total benefit from Colorado River water where (economically feasible) alternatives are not available. Because the agricultural benefit functions given in Table 1 hold only for $x/x_0 \geq 50$ percent, total benefit functions cannot be found solely from Equation (2). For agricultural users, the average benefit of water use $\bar{v}$ in \$/af is available, however. The total benefit $V_a(x)$ of use x can then be expressed as

$$V_a(x) = x_0\bar{v} - x_0 p_0 \int_x^{x_0} (x'/x_0)^\alpha\, dx' \tag{4}$$

where $x_0\,\bar{v}$ is the total benefit at full requests x_0, and the integral gives the loss suffered by the irrigator from deliveries below x_0. Evaluating the integral gives

$$V_a(x) = x_0\, (v_0\, (x/x_0)^\beta + \bar{v} - v_0) \tag{5}$$

The marginal benefit functions (Equation 2) and elasticities are not altered by addition of the constant $x_0\, (\bar{v} - v_0)$ to Equation (3).

RECREATION DEMAND

Water-based recreation is an important part of many Westerners' leisure activities, and water-related recreation opportunities draw visitors and tourism dollars to the western United States. Instream flows are vital in preserving fish and wildlife habitat in the arid West and in endangered species restoration. As diversions of water for offstream irrigation and for industrial and residential deliveries have increased, flow levels on many stream systems have decreased to the detriment of instream water uses. The droughts of the 1980s focused further attention on the negative effects of depleted streams and lake levels for recreation, fish, and wildlife.

Measuring Economic Impacts of Instream Flow Protection

Policy makers can make more informed decisions about stream and reservoir management and water allocation if they know the economic benefits provided by a stream system for various activities such as angling and whitewater rafting. Information on the effects of specific changes in water levels also is desirable when considering the economic impacts of drought-induced changes in stream flows and reservoir levels. Since there is limited direct-market evidence on willingness to pay for water-based recreational opportunities and for fish and wildlife preservation, a variety of valuation approaches have been applied to estimate the value of water for these purposes. Marginal benefit functions for recreation can be estimated using information on recreationists' expenditures to travel to and enjoy a water-based recreation site by using the travel costs method (TCM). Alternatively, data can be elicited from recreationists regarding their willingness to pay for recreational use of a river at differing flow levels by using the contingent valuation methods (CVM). The TCM has been used for decades to infer the value that visitors to a recreation area put on the site. The CVM has been refined and applied widely during the past decade to estimate benefits associated with site use and changes in site quality, including changes in flow levels. CVM also is used to measure willingness to pay for preservation that is not associated with actual use of an area. These non-use values arise as people experience benefits from preserving a site or a species that are not associated with a visit to the site or with viewing the species. Estimation of non-use values, which may be quite large, is outside the scope of this research (see Brookshire *et al.*, 1986; Cummings *et al.*, 1986; and Sanders *et al.*, 1990; for discussions of CVM and non-use values). Cummings and Harrison (1995) discuss the components of non-use values.

Reservoir Recreation Benefits

Although water-based recreation resources provide substantial non-market benefits to users, reservoir recreation has received little attention relative to other water uses. Reservoir operations have been primarily aimed at meeting water demands for consumptive uses and power generation, and few studies have attempted to assess the impacts of reservoir level fluctuations on water-based recreation opportunities.

Use of Basin reservoirs is believed to be a declining function of reservoir content or area. Little empirical work has been done in this area, however. One study by Ward and Fiore (1987) of visitation to New Mexico reservoir sites used the square root of reservoir area as an explanatory variable for observed differences in visitation at different reservoirs. No attempt was made to examine the impact of changes in reservoir levels over time with changes in visitation, however. Simple models of Colorado River Basin visitation data for 1980-1992 did not provide a basis for adopting any specific functional relationship, perhaps because of inadequate representation of substitute sites or because of limited reservoir fluctuations over a time period of increasing demand for recreational opportunities (and changes in reporting procedures). We have assumed, for purposes of this study, that visitation at each Basin site declines as the square root of the volume of each reservoir but that use benefits for each visitor are unchanged as reservoir level changes.

Annual visitation to seven Colorado River Basin reservoirs is estimated at 17 million visitor days, based on data provided by the Glen Canyon National Recreation Area (Gediman, personal communication, 1993) and the Lake Mead National Recreation Area (Warner, personal communication, 1993) and supplemented by the Upper Colorado River Commission (1992). Visitors typically engage in boating, fishing, and swimming. The economic benefits received by visitors to Basin reservoirs were estimated using existing studies of use values at specific Basin reservoirs supplemented by a literature summary (Walsh *et al.*, 1988). An average visitor day value for each reservoir was developed using separately calculated values for fishing and all other uses. The average recreational value per visitor day at each reservoir was then found as the weighted sum (weights based on data from Gediman and Warner) of values from each activity. Data sources and recreation visitor day values at Basin reservoirs are summarized in Table 3. In many cases alternative estimates of visitor day values are available for specific sites [e.g., Johnson and Walsh (1987) for Blue Mesa reservoir] which give similar values per visitor day to those reported here. In all cases the final estimated values are similar to the averages reported by Walsh *et al.* (1988).

Free Flowing Reach Recreational Benefits

Recreational use for fishing, boating, and hiking on free flowing reaches (defined here as those not impounded by reservoirs) of the Colorado River mainstem and tributaries also provides economic benefits to users. Because comprehensive data on the dependence of use levels and economic benefits to users on river flows is limited, this study only provides benefit estimates for use between Glen Canyon Dam and Lake Mead.

Recreation below Glen Canyon Dam is dominated by day users rafting and fishing in the relatively calm reach 15 miles below the dam and above the Lees Ferry boat launch, and by multi-day whitewater rafting trips through the Grand Canyon. A study commissioned by the Department of Interior (Bishop *et al.*, 1989) as a part of the Glen Canyon Environmental Studies (a multi-agency study effort providing information on the impacts of Glen Canyon Dam operations) indicates that benefits generated by whitewater rafting and fishing (day use) are significantly influenced by river flow levels. The study used the CVM and found that benefits per fishing day reach their peak of $51/visitor day at a constant flow level near 10,000 cubic feet per second (cfs) and that fluctuations in flows (which occur when peaking hydropower is generated) cause a decrease in fishing benefits. For comparison, Richards and Wood (1985) found fishing benefits at Lees Ferry of $170/visitor day in a TCM study. Fluctuations in flow levels also have a negative impact on benefits experienced by whitewater rafters, with relatively high steady flows (around 30,000 cfs) generating maximum benefits of $122/visitor day for whitewater boaters. Using the findings of Bishop *et al.* (1989) quadratic equations with total benefits V (in $/visitor day) expressed as a function of river flows Q (in kaf/year) were fit to the point estimates of use values:

TABLE 3. Annual Economic Benefits of Flatwater Recreation at Basin Reservoirs (1992 dollars).

Reservoir	Visitation (million/year)	Fishing ($/day)	Weight	Other ($/day)	Weight	Total ($/day)
Flaming Gorge	1.65	12.04[1]	0.5	21.21[2]	0.5	16.63
Curecanti Unit	0.78	29.22[3]	0.4	21.21[2]	0.6	24.41
Navajo	0.59	29.22[3]	0.4	21.21[2]	0.6	24.41
Powell	3.20	29.22[3]	0.2	24.21[4]	0.8	25.21
Mead	6.76	30.17[5]	0.2	36.16[6]	0.8	34.96
Mohave	2.05	30.17[5]	0.2	36.16[6]	0.8	34.96
Havasu	1.99	30.17[5]	0.2	36.16[6]	0.8	34.96

[1]Oster *et al.* (1989).
[2]Average of picnicking and swimming values (Rocky Mountains and Southwest) reported by Walsh *et al.* (1988) (Table 4).
[3]Average of flatwater fishing values reported by Gordon (1970), Sorg *et al.* (1985), and Ward and Fiore (1987).
[4]Average of motorized boating values for California given by Wade *et al.* (1988) and picnicking and swimming values reported by Walsh *et al.* (1988).
[5]Value for general anglers at Lake Mead reported by Martin *et al.* (1982).
[6]Motorized boating values on Lake Havasu given by Wade *et al.* (1988).

$$V_{fishing}(Q) = 23.6 + 5.76 \times 10^{-3}\,Q - 2.69 \times 10^{-7}\,Q^2 \quad (6)$$

$$V_{rafting}(Q) = -12.3 + 11.4 \times 10^{-3}\,Q - 2.41 \times 10^{-7}\,Q^2 \quad (7)$$

R^2 for Equations (6) and (7) were 0.99 and 0.98, respectively. Total benefits in each activity are found by multiplying the per visitor day benefits by 15,000 and 169,000 annual visitor days for day use fishing and multi-day rafting, respectively.

The focus on this single reach (located mostly within Grand Canyon National Park) likely results in a serious underestimation of the total instream use values in free flowing reaches. For example, visitor days on the single reach for which we estimate benefits total about 175,000 annually, while data provided by Rosene (Bureau of Land Management, Upper Colorado River District Office, Kremmling, personal communication, 1993) and Von Koch (Bureau of Land Management, Moab District Office, personal communication, 1993) identify over 130,000 visitor days on raft trips in the Westwater, Desolation Canyon, San Juan River, and Upper Colorado River reaches, half as part of multi-day trips. Day trips to raft Westwater Canyon on the Colorado River mainstem are valued at over $200 per trip by using TCM (Bowes and Loomis, 1980). Fishing and shoreline uses are also important throughout the region. For example, an individual's willingness to pay ranges up to $60/day [estimated by Daubert and Young (1981) using CVM] for fishing on the Cache la Poudre, an eastern Colorado mountain river affected by Basin water exports. Flow levels are important: anglers' and shoreline users' aggregate marginal benefits from additional flows range from $23 and $6/af, respectively, at relatively low flow, but are negative at high flow levels. Because such data on the relationship between instream flows and recreation values in Basin reaches is very limited, however, no further benefit functions are developed.

HYDROPOWER

Instream flows, largely from reservoir storage, produce hydroelectric power at a number of Basin dams. Estimates of the marginal value of generated hydropower were prepared based on the avoided cost of alternative thermal energy production. Hydropower production occurs during base and peak load periods, displacing base load (primarily coal and nuclear) facilities and peak load (primarily gas turbine) facilities, respectively. Because the cost of peaking production is typically significantly greater than for base load production, hydropower plants are often operated to maximize total production during peak periods.

Hydropower production in the Lower Basin during peak load periods is largely constrained by plant capacities. The physical effect of marginal decreases in water flow is then dominantly a decrease in base load production, with peaking production unchanged. The marginal value of Lower Basin hydropower is conservatively valued at the avoided cost of base load production at thermal facilities.

Upper Basin hydropower production is modeled after the preferred alternative given in the 1995 Final

Environmental Impact Statement on operation of Glen Canyon Dam (U.S. Bureau of Reclamation, 1995). Under the "Modified Low Fluctuating Flow Alternative," base and peaking releases are effectively constrained by a maximum allowable daily flow fluctuation. Marginal reductions in total flow thus reduce both base and peaking production. Because base and peaking periods are roughly equal in length (Harpman *et al.*, 1994), Glen Canyon hydropower can be valued at the mean avoided cost of base and peaking period alternatives. Other Upper Basin hydropower is valued similarly.

Generation costs for base and peaking periods for each Basin are taken from Booker and Young (1991). Only operations and maintenance costs were used given the presence of substantial underutilized thermal capacity serving the market for Basin hydropower. As an approximation to modeling operation of generation and transmission through a complex, interconnected grid in replacing hydropower generation (U.S. Department of Energy, 1994), the most costly 50 percent of total installed capacity serving the Upper and Lower Basins was used as the basis for these avoided cost calculations. Costs of operating Basin hydropower facilities were not determined, though they are both small (e.g., maintenance costs for investor-owned utilities reported by U.S. Department of Energy (1992) are 2.8 mills/kwh) and to some extent independent of the total level of hydropower production (and hence do not contribute to marginal costs). Net marginal benefits of hydropower production based on avoided cost and operating expenses were estimated at 52.4 and 46.9 mills/kwh for the Upper and Lower Basins, respectively.

Net benefits in units of instream flow (i.e., $/af) are found by calculating total energy production using

$$E = k\,h\,Q\,\eta \tag{8}$$

where h is the hydropower head (in feet), k is a constant 1.02353 kwh/af/foot of head, Q is the total instream flow (excluding spills, in af), and η is the system efficiency for electric generation. Efficiency was estimated at 0.9 for all Basin reservoirs, while the hydropower head depends directly on reservoir conditions. Table 4 gives the net marginal benefits of instream flows estimated under the typical Basin conditions characterizing the first nine years of a particular drought sequence (Booker, 1995).

CONVEYANCE COSTS

Marginal conveyance costs are dominated by the energy costs of pumping lifts required to deliver Basin water to southern California municipal uses, Central Arizona, and several smaller users. Energy costs are estimated by the marginal costs of Basin electrical energy production. Following the approach to valuing hydropower production, the operation and maintenance cost of thermal sources is used to value energy usage. Again, the most costly 50 percent of installed capacity is used as the appropriate measure of marginal costs. Flow-related maintenance expenses estimated for hydropower production are utilized for non-energy marginal operation and maintenance costs. Such expenses would result primarily from maintenance of pump motors and turbines. Valuing conveyance costs from such a national economic perspective gives marginal costs for pumping of water for agricultural uses ranging from $10/af for Navajo Indian Irrigation Project users to $87/af for CAP. Municipal conveyance costs were estimated at $107/af for MWD users and an average $123/af for CAP users.

TABLE 4. Annual Economic Benefits of Instream Use at Basin Dams and Reservoirs. Year 1 of severe and sustained drought simulation (Booker, 1995) (1992 dollars).

	Hydropower Benefits		Recreation Benefits	
Dam and Reservoir	Total ($ million)	Marginal ($/af)	Total ($ million)	Marginal (annual $ per af of storage)
Flaming Gorge	18	19.8	23	8.7
Curecanti Unit*	109	45.2	17	19.5
Navajo	24	17.0	12	10.0
Glen Canyon Dam/Lake Powell	223	26.3	71	3.7
Hoover Dam/Lake Mead	201	23.6	199	10.4
Davis Dam/Lake Mohave	46	5.8	72	39.6
Parker Dam/Lake Havasu	23	3.3	70	112.4

*Composite of Morrow Point, Blue Mesa, and Crystal Dams.

SALINITY DAMAGES

Colorado River salinity first became a major issue when irrigation return flows from the Wellton-Mohawk division of the Gila Project in Arizona resulted in water deliveries to Mexico with concentrations as high as 2,700 mg/l (Miller *et al.*, 1986). Construction of a drainage canal to the Gulf of California reduced concentrations in Mexican deliveries to near those used by Arizona and California irrigators, but drainage water could no longer be included in the 1.515 million acre-feet delivered annually to Mexico. Salinity in Colorado River water is believed to cause substantial damage to United States municipal and agricultural water users as well. Indeed, with the recent completion of the Central Arizona Project delivering municipal supplies to Phoenix and Tucson, an additional 2.5 million water users are now potentially affected by Colorado River salinity.

Damage estimates are problematic, however, given the differing composition of mineral constituents at different locations and the long time period over which damages are believed to occur. One set of damage estimates presented by Booker and Young (1991) is used here to provide an estimate of salinity damages to municipal and agricultural users. Constant marginal damages over time are assumed. The municipal damage estimate is based on the single household damage estimate of $0.26 per mg/l (1989 dollars) given in Booker and Young (1991). Assuming two households per acre-foot of water use, damages are $0.558/mg/l/af expressed in 1992 dollars. Municipal damages are assumed for Las Vegas, CAP (municipal), and MWD users. Agricultural damages are based on producer income differences in linear programming models of Imperial Valley (California) agriculture at 800 mg/l and 1100 mg/l salinity (Booker and Young, 1991). Salinity damages from full water deliveries to 50 percent reductions are within 10 percent of the average value of $0.0378/mg/l/af (1992 dollars). The latter is used to estimate damages to agricultural water users in Arizona and California.

While these damage estimates are typical of those used by other researchers, they should be regarded as preliminary. For example, the municipal damage estimate suggests damages of $130/af from use of Colorado River water based on salinity concentrations of 675 mg/l in Colorado River water and 415 mg/l in an alternative supply. Coupled with high conveyance costs for some uses, this suggests small net marginal benefits from Colorado River water use in several cases. The recent negative public reaction to introduction of Colorado River water in Tucson supports this view, as does the reluctance of central Arizona farmers to use CAP water. Nevertheless, unabated efforts to secure additional Colorado River supplies by southern California and southern Nevada suggest that water providers will accept salinity damages when they lack alternative cost effective water sources.

CONCLUSION

The economic benefit and cost estimates for offstream and instream water use provided in this article encompass all major water uses in the southwestern United States. The estimates provide a basis for policy decisions affecting southwestern United States water users and for policies governing the Colorado River, which currently are the subject of intense political negotiations and debate. In providing benefit estimates across a wide variety of competing uses, the inevitable tradeoffs in allocating water resources across the Southwest are clarified. The economic impacts of drought reported by Booker (1995) and Henderson and Lord (1995) elsewhere in this issue explicitly address tradeoffs exacerbated by the presence of drought.

Despite our focus on the dominant economic impacts of regional water use, these benefit estimates do not include non-use values. Hence significant environmental values not based on direct resource use (e.g., protection of endangered species) are not addressed. Second, indirect economic impacts of water use are not considered. Total regional economic impacts could thus significantly exceed the direct economic impacts calculated based on our benefit estimates. Finally, benefit estimates in every offstream and instream use contain large uncertainties and are subject to continued refinement as additional data becomes available. Nonetheless, the estimates given here are based on detailed research covering the value of water in both offstream and instream uses, and they provide a reasonable starting point for reconciling the competing needs of these alternative water uses.

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HYDROLOGIC AND ECONOMIC IMPACTS OF DROUGHT UNDER ALTERNATIVE POLICY RESPONSES[1]

James F. Booker[2]

ABSTRACT: A severe sustained drought in the Colorado River Basin would cause economic damages throughout the Basin. An integrated hydrologic-economic-institutional model introduced here shows that consumptive water users in headwaters states are particularly vulnerable to very large shortfalls and hence large damages because their rights are effectively junior to downstream users. Chronic shortfalls to consumptive users relying on diversions in excess of rights under the Colorado River Compact are also possible. Nonconsumptive water uses (for hydropower and recreation) are severely affected during the worst drought years as instream flows are reduced and reservoirs are depleted. Damages to these uses exceeds those to consumptive uses, with the value of lost hydropower production the single largest economic impact of a severe sustained drought. Modeling of alternative policy responses to drought suggests three general policy approaches with particular promise for reducing damages. Consumptive use damages can be reduced by over 90 percent through reallocation from low to high valued uses and through reservoir storage strategies which minimize evaporation losses. Reservoir management to preserve minimum power pool levels for hydropower production (and to maintain reservoir recreation) may reduce damages to these nonconsumptive uses by over 30 percent, but it may increase consumptive use shortfalls.
(KEY TERMS: economic impacts; drought; water policy; reservoir management; institutions; modeling.)

INTRODUCTION

Seven states in the southwestern United States utilize Colorado River Basin water resources. The region's agriculture is totally dependent on irrigation, with Basin water typically the sole irrigation supply. Water from the Colorado River mainstem and its Colorado tributaries accounts for nearly 40 percent of the water supply for the largest population center in each of four western states, including California (Booker and Colby, 1995). Las Vegas, the largest city near the river, is almost wholly dependent on river supplies and has few viable alternatives. Regional energy production utilizes instream flows directly for hydropower generation and requires Basin water for cooling at thermal plants. These same instream flows, and water stored in Basin reservoirs, provide recreational opportunities throughout the year to regional, national, and international visitors.

While alternatives to Colorado River supplies exist, they are limited or prohibitively costly, or both. The Colorado River and its tributaries are the critical resource enabling residents of the Southwest to transform an arid landscape. An extreme drought extending over several decades could be expected to result in exceptional impacts to a system so dependent on a single water supply. One purpose of this work is to develop detailed, quantitative estimates of the economic damages of a specific, hypothetical drought (more severe than any from the historical record) on consumptive and nonconsumptive users of Basin water resources. Damages are estimated here by modeling the existing system of reservoirs and the water allocation institutions governing reservoir management and water deliveries. No additional water storage facilities and no water transfers from low to high valued uses during drought are included under this baseline scenario, severely restricting possible responses to drought.

While little can be done to prevent the occurrence of drought, policies for managing Basin water resources might greatly influence the consequences of drought. Water users have long recognized the risks in depending on a highly variable resource such as the Colorado River. One response in the Colorado River Basin has been the construction of a number of

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storage reservoirs; capacity in Basin reservoirs is now four times the mean annual inflow, sufficient to provide carryover storage for many years. Recognizing that values in consumptive uses may vary by factors of ten or more within the Basin (Booker and Colby, 1995), advocates of water markets have pointed to potential gains from trade as an additional or alternative approach to dealing with Basin water scarcity. In response, some Basin states (e.g., California, in response to drought) have introduced limited water "banks," or markets to more efficiently distribute limited supplies. Griffin and Hsu (1993) point out, however, that in the absence of institutions representing instream flow values, water markets will likely fail to maximize economic benefits from trade.

Our second purpose is to investigate potential benefits from relaxing the assumption that drought would be managed under existing rules. In addition to suggested management, alternatives consistent with the current general policy framework known as the Law of the River (e.g., MacDonnell *et al.*, 1995), policies altering traditional water rights structures, those which reserve water for instream uses, or those allowing interstate consumptive use markets are investigated.

An integrated hydrologic-economic-institutional model (CRIM, the Colorado River Institutional Model) for estimating the economic and hydrologic impacts of drought is first introduced. Second, model results are used to develop a detailed assessment of economic impacts of the severe sustained drought under the existing operating rules and policy (the Law of the River). The economic and hydrologic impacts reported are derived directly from the use of CRIM to model the severe sustained drought under this existing River management. Eight alternative policy responses to drought are then modeled. Drought impacts under each policy are critically examined, and several recommendations are provided.

MODEL DESCRIPTION

An integrated economic-hydrologic-legal model was developed for this study to estimate economic impacts of alternative water allocations and to investigate impacts of policy responses to drought. Termed the Colorado River Institutional Model (CRIM), it expands on an earlier Basin model reported by Booker and Young (1994) by adding more realistic hydrology, utilizing less aggregated economic data, and modeling with a richer set of institutional choices. While numerous recent modeling efforts examine economic impacts of variable flow levels in the Basin [see Brown *et al.* (1990), Oamek (1990), Lee *et al.* (1993), Brookshire *et al.* (1993), and Henderson and Lord (1995)], CRIM focuses on modeling the water allocation problem under a range of non-market and market-based institutions.

CRIM model components include 24 river nodes, seven reservoirs (including active and dead storage, evaporation, hydropower production and benefits, and flatwater recreation benefits), 32 consumptive use locations, two instream flow uses (Glen Canyon and Grand Canyon), and 14 inflow points. Figure 1 summarizes the model design.

Water allocation and economic benefits of water use are determined on an annual basis. Reservoir storage levels, including salinity loads, are carried from one annual time step to the next. The model is not forward looking, except to the extent that institutional allocation rules may include trigger points for water use reductions when reservoir storage or elevations decline below set levels. The sequential decision making followed by CRIM facilitates the modeling of existing Basin institutions and comparison with other Basin models. Hurd, Callaway, and Smith (RCG, Inc., Boulder, Colorado, 1995) have prepared a dynamic formulation of CRIM. Decision variables are generally limited to water use at all Basin locations, and reservoir releases. Flow and salinity levels, reservoir storage, and economic impacts are the state variables which describe the resulting system. CRIM is written in GAMS (Brooke *et al.*, 1988) and solved using its MINOS nonlinear solver. A typical simulation of a 38-year drought sequence requires 30 minutes using a Gateway 486 DX-33.

Nine alternative policy responses to drought were developed within CRIM, including, as the base case, the existing "Law of the River." Each individual policy response could generally be instituted at any time; several are independent and could be utilized in combination. In the work described below, policy responses are investigated when hydrologic conditions reach predetermined trigger points.

CRIM Under the Law of the River

CRIM is formulated as an optimization problem, nonlinear in the objective function and constraints. Hydrologic and economic factors are included as constraints, while institutional factors are primarily (though not exclusively) simulated in the objective function. Colorado River Basin water resources are allocated under a complex set of interstate compacts, federal laws, court decisions, administrative rules, and a treaty between the United States and Mexico, known collectively as the Law of the River. The set of allocation rules can be interpreted as determining a priority system for the use of Basin water resources.

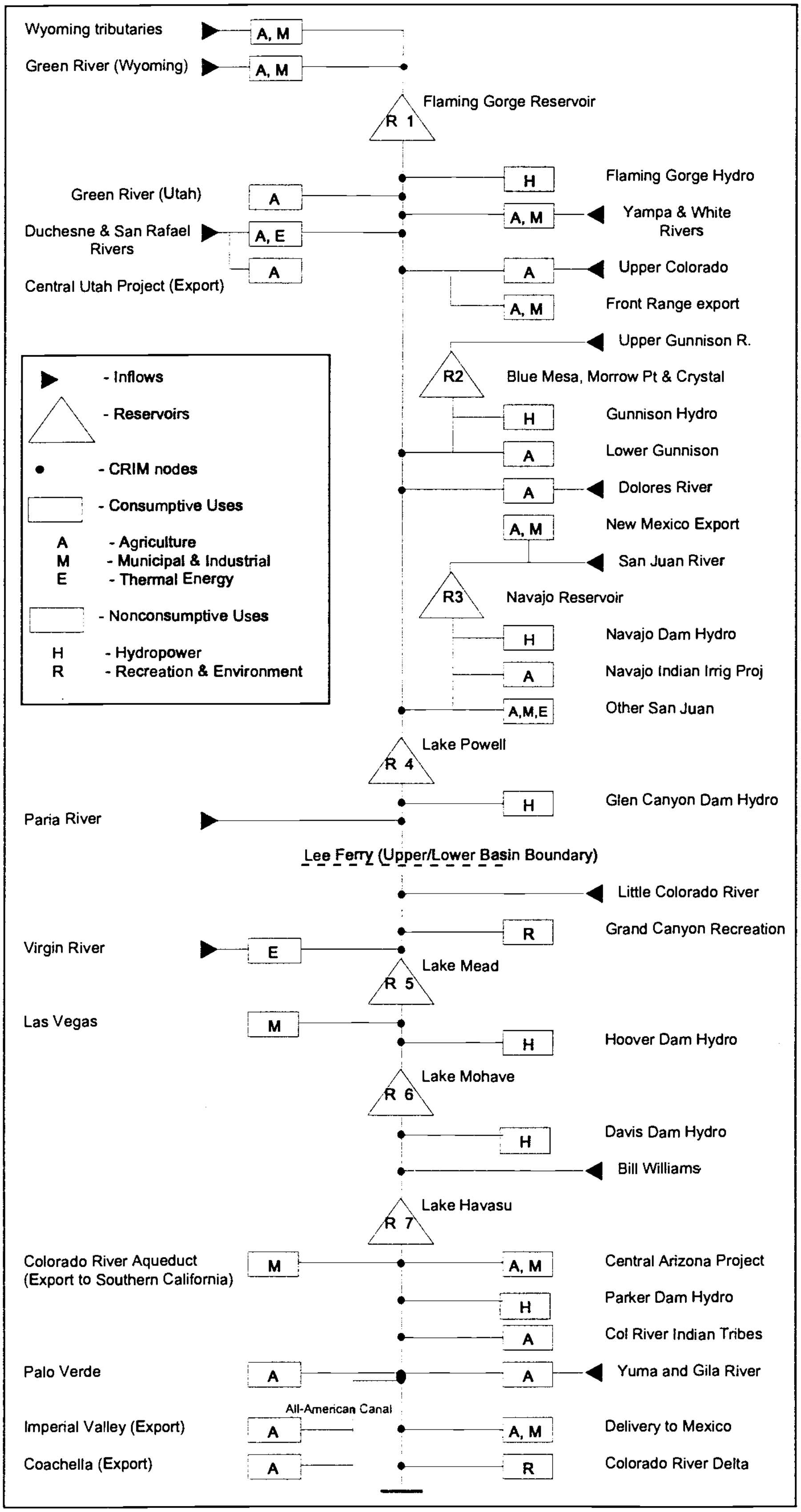

Figure 1. Colorado River Basin as Represented by the Colorado River Institutional Model (CRIM).

The set of priorities utilized by CRIM can be summarized as follows, from highest to lowest priority:

1. Mexican delivery obligation.
2. Upper Basin consumptive use rights perfected prior to the 1922 Colorado River Compact.
3. Lee Ferry delivery ("annual objective release");
4. Remaining Upper Basin consumptive use.
5. Lower Basin consumptive use, exclusive of priorities (6) and (8) below.
6. Metropolitan Water District (MWD) surplus diversions.
7. Storage in Lake Mohave and Lake Havasu.
8. Central Arizona Project (CAP) normal diversions (surplus diversions are not modeled).
9. Upper Basin storage.

Objective Function. The priorities for use of Colorado River water resources under the Law of the River policy lead directly to one form of the objective function $V(X_p, X_u)$ used by CRIM:

$$V(X_p,X_u)=\sum_p \alpha_p X_p - \beta\, T_u \left[\left(\sum_s (X_s - \rho_s X_u)^2\right)\right]^{1/2} \tag{1}$$

where X_p is the annual "use" (consumptive use, instream flow, or addition to storage) associated with priority p, X_s is the annual consumptive use level for each Upper Basin state s, X_u is the total annual consumptive use by all Upper Basin states, ρ_s is the percentage allocation to each under the 1948 Upper Colorado River Basin Compact (Upper Basin Compact), and T_u is the total annual shortfall to Upper Basin consumptive users. Arizona's Upper Basin uses of up to 50 thousand acre-feet (kaf) per year are not included, given the seniority of such use under the Upper Basin Compact. The weighting constants α_p and β, are based on the priorities p listed in the previous section. The constants are ordered such that $\beta > \alpha_p$ and $\alpha_p > \alpha_{p+1}$, where priority (seniority) decreases with increasing p. The square root of the last term in Equation (1) is taken to facilitate convergence of the solution algorithm. Changes utilized under specific alternative policy responses are described below.

If Upper Basin consumptive uses cannot be fully satisfied, then $T_u > 0$ and consumptive use in each state is based on its share under the Upper Basin Compact. Arizona's Upper Basin annual use is the smaller of 50 kaf or its full request for Basin water. Proportional reductions across all uses within each state are required when requests for Basin water cannot be fully satisfied. So-called "prior perfected rights" existing prior to the full Basin Colorado River Compact are protected by placing a constraint on Upper Basin use $X_u \geq \overline{X}_u$ where $\overline{X}_u$ is set at the estimated annual level of such rights of 2,000 kaf. Water use in southern California by the MWD above its existing water rights (including transfers from the Imperial Irrigation District and the Palo Verde Irrigation District) is not permitted unless surplus conditions (total storage above 25.0 maf) prevail in Lake Mead. Similarly, annual deliveries to Arizona's Central Arizona Project (CAP) are limited to 450 kaf when the elevation at Lake Mead is less than 1095 feet (shortage conditions).

Annual reservoir releases for consumptive use or storage at downstream reservoirs are determined by the so-called equalization rule. This is implemented by a set of constraints which give priority to Lower Basin storage, while requiring equal proportional drawdown of Upper Basin reservoirs.

Hydrologic Constraints. Water and salt flows as well as reservoir water and salt levels are dependent on water and salt inflows, and on water use and reservoir levels, the decision variables. Mass balance constraints give annual water flows Q_i (kaf/year) leaving node i

$$Q_i = Q_{i-1} + q_i + R_i - X_i \tag{2}$$

where q_i and R_i are net inflows and reservoir releases between i and i-1, respectively, and X_i is the total consumptive use (including exports) from i. Mainstem withdrawals and return flows are not explicitly modeled using this framework; this is a reasonable approximation here, where withdrawals are small relative to total flow levels and return flows occur near the point of withdrawal. Net reservoir releases R_i are the difference between the initial active storage levels minus evaporation, and final active storage levels in each annual time step.

Salt flows (thousand tons/year) are estimated using a similar mass balance approach assuming constant salt inflows over time. Consumptive uses within the Basin thus neither contribute to nor diminish salt loading, although salinity concentrations increase with consumptive use as dilution decreases. While unrealistic, there is little systematic data on the relationship between water use (or withdrawals) and salt loading for the full Basin. For an illustration of the relationship between water use practices and resulting salt loading for one specific Basin location, the Grand Valley in Colorado see Gardner and Young (1988). Full mixing of salts in Basin reservoirs is assumed during any given year.

Intertemporal Model Operation. The storage capacity of Basin reservoirs is approximately 60 maf, four times the total average annual inflow to the Basin. Carryover storage from one year to the next is the critical reservoir function in the context of this study. Intertemporal reservoir accounting is maintained by calculations outside the optimization model to reduce model nonlinearities. Reservoir active and dead storage levels are utilized prior to each annual optimization to calculate elevations and areas. Elevation and area are in turn used to estimate annual evaporation and average hydropower heads, respectively. The optimization model is then solved using fixed evaporation and heads, together with the inflow and depletion requests for the particular year. Reservoir water and salt levels given by the model solution are then used to determine the new inputs for the following year's optimization problem.

Reservoir Area and Elevation Calculations. Reservoir areas and elevations are calculated before each optimization using formulas derived from those used in the USBR (1986) Colorado River Simulation Model (CRSM). A simplified piecewise approach was utilized for both area and elevation calculations. Above dead storage contents, a single quadratic approximation to the piecewise cubic fits used by CRSM was made. A single linear approximation was used below dead storage levels. Critical reservoir elevations and contents (dead storage, minimum power pool, maximum power, and maximum storage) reported by the Upper Colorado River Commission (1992) were used.

Use of Existing Basin Databases. Three Basin databases are utilized by CRIM. Depletion requests initially developed by USBR (1991) and discussed in detail by Booker and Colby (1995), drought inflows to 29 Basin locations (Tarboton, 1995), and historic salt levels at 20 Basin locations reported under the Colorado River Basin Salinity Control Program comprise the hydrologic data.

Depletion Requests. Present and future requests for consumptive use depletions by Basin users follow the USBR's CRSM water demand and inflow data sets (USBR, 1991), adjusted to reflect reasonable future conditions (Booker and Colby, 1995). High, medium, and low projections of future depletion requests were made based on assumptions of Basin population growth, agricultural water use, and demand for energy products. The medium scenario used for the simulations reported here reflects the USBR depletion projections with three major exceptions. Requests for agricultural water depletions are projected to remain constant at present levels. Central Arizona Project annual diversions are limited to 450 kaf under Lower Basin shortage conditions. Las Vegas requests for diversions are assumed to grow without institutional bounds based on projected population levels.

Depletion requests in the basic data set are given for 256 distinct depletion points. These points are aggregated to a total of 32 consumptive use locations for use in CRIM. Attributes associated with each use are Upper or Lower Basin, state, Basin use or export, type of use (agricultural, municipal, energy), and economic demand function. The demand function is specified on a consumptive use basis. CRIM scales the total benefit function associated with each economic demand function to a depletion schedule as described by Booker and Colby (1995). Table 1 summarizes the consumptive use depletion points and their attributes.

TABLE 1. Attributes of Colorado River Consumptive Use Locations in the Colorado River Institutional Model (CRIM).

Depletion	Primary Use[1]	Location[2]	Economic Demand Function
WYa1	A	UB	Wyoming Agric
WYa2	A	UB	Wyoming Agric
WYm2	E	UB	Energy
UTa1	A	UB	Utah Agric
WYa3	A	UB	Wyoming Agric
COa1	A	UB	Colorado Agric
COe1	E	UB	Energy
UTa2	A	UB	Utah Agric
UTa3	A	UB	Utah Agric
UTe1	E	UB	Energy
COa2	A, X	UB	Front Range Agric
COm2	M, X	UB	Front Range Muni
COa3	A	UB	Colorado Agric
COa4	A	UB	Colorado Agric
COa5	A	UB	Colorado Agric
COa6	A	UB	Colorado Agric
AZub	A	UB	New Mexico Agric
NMa1	A, X	UB	San Juan-Chama Agric
NMm1	M, X	UB	San Juan-Chama Muni
NMa2	A	UB	NIIP Agric
NMe1	E	UB	Energy
NMa3	A	UB	New Mexico Agric
VNe1	E	LB	Energy[3]
NVm1	M	LB	Las Vegas Muni
CAm1	M, X	LB	MWD Muni
AZa1	A, X	LB	CAP Agric
AZm1	A, X	LB	CAP Muni
AZa2	A	LB	Col River Indian Tribe Agric
CAa1	A	LB	California Agric
CAa2	A, X	LB	California Agric
CAa3	A, X	LB	California Agric
AZa3	A, X	LB	Yuma Agric

[1]A=agriculture, M=municipal and industrial, E=thermal energy, X=export from the Basin.
[2]Use is located in the Upper Basin (UB) or the Lower Basin (LB).
[3]Virgin River use, primarily in Utah.

Water and Salt Inflows. The 29 water inflow points used by CRSM (USBR, 1991), aggregated to 14 inflow locations, are used by CRIM. A drought sequence developed by Tarboton (1995) and described below was utilized. Basin salt inflows were estimated from the average historical salt loads at 20 Basin locations reported by U.S. Department of Interior (1989). Salt loads are converted to inflows for use by CRIM and then aggregated to the 14 source locations utilized for water inflows. Variation of salt inflows with water level was not investigated.

Model Verification

CRIM provides annual estimates of water use and benefits, flows, storage, and evaporation which closely match those of Hydrosphere's Colorado River Model (Harding *et al.,* 1995), which in turn follow those of USBR's CRSM model. Reservoir storage is a sensitive measure of overall model performance because systematic differences in consumptive use estimates or aggregate Basin evaporation are integrated over time. Figure 2 compares CRIM and Colorado River Model (CRM) estimates of total storage in the major Basin reservoirs (Lake Powell and Lake Mead) when hydrologic inputs and requests for consumptive use depletions are identical, using the 38-year drought sequence described below. The CRIM estimate of increasing reservoir depletion lead those of CRM by less than one half year at year 20. In the final year of the modeled drought (year 38), the CRIM estimate of Basin storage is within 6 percent of the CRM estimate. The small differences which occur are related to differing interpretations of CAP deliveries under shortage conditions.

IMPACTS UNDER THE LAW OF THE RIVER

Drought impacts under the Law of the River are presented in this section. Three distinct drought periods are identified, with specific impacts characterizing each period. Hydrologic impacts are summarized to provide a context for interpreting economic impact estimates. Damages to consumptive uses from the severe and sustained drought and total drought damages, including hydropower production losses, recreation losses, and salinity damages, are presented.

Severe and Sustained Drought Impacts Under the Law of the River

The single drought utilized in this study is embedded in the 38-year flow sequence discussed in detail by Tarboton (1995). The sequence represents one estimate of the worst extended drought occurring during the past 500 years. The average annual

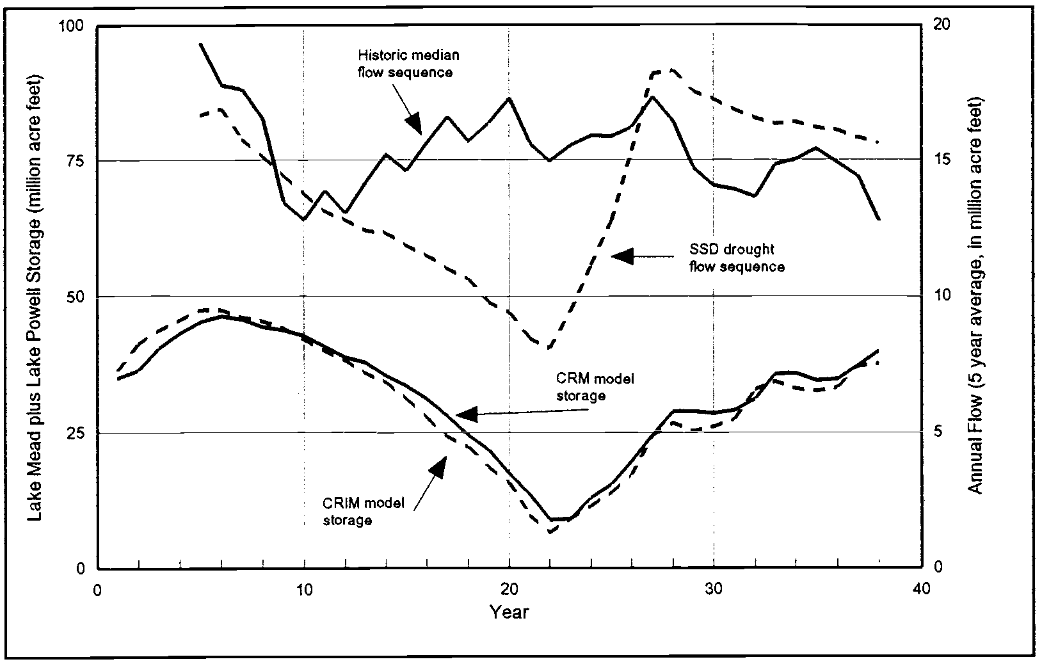

Figure 2. Severe and Sustained Drought (SSD) Flow Sequence (top, right scale) and the Resulting Combined Lake Powell and Lake Mead Contents from CRIM and CRM (Harding *et al.,* 1995).

naturalized flow over the full sequence is 14.2 maf/year, compared to 15.4 maf/year for the median 38 years from the historical record (Figure 2). However, Basin inflows average only 9.3 maf/year in the driest 10 years of the drought sequence. Economic impacts are summarized in Figure 3.

Baseline: Years 1 through 9

The initial nine years of the full 38-year drought sequence serve as a base period for establishing typical hydropower and recreation benefits and salinity damages. Basin inflows average 15.5 maf/year, while storage in Basin reservoirs increases from 46 maf to 52 maf, with a peak of over 56 maf in year 6. Benefits of hydropower production average roughly $600 million per year during this period, while recreation benefits average $500 million. Damages to consumptive water users (agricultural and municipal) from salinity average $250 million per year. These levels give representative benefits and damages from nonconsumptive use of Colorado River water resources under typical river conditions and establish a base level of benefits and costs for use in measuring

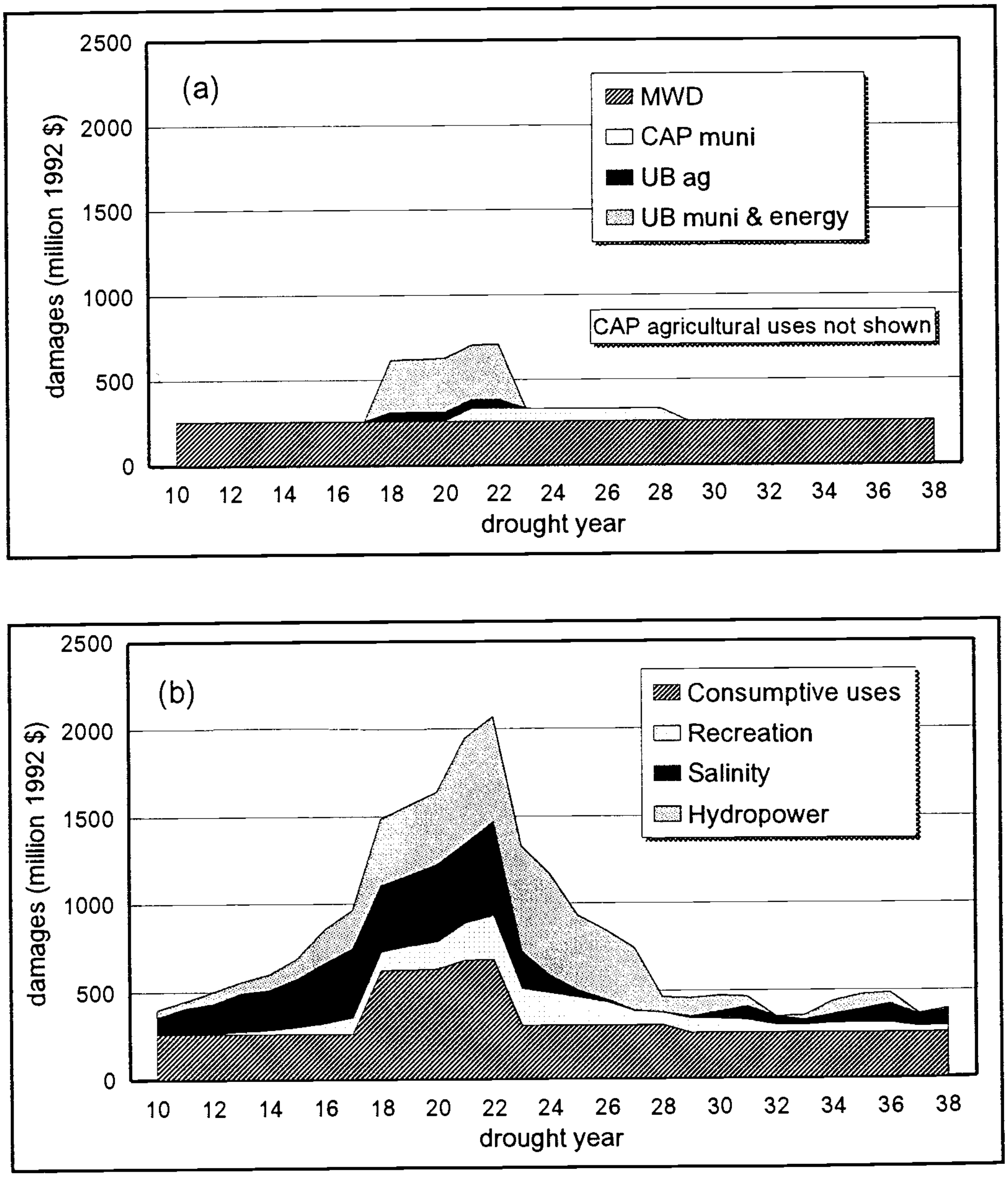

Figure 3. Consumptive Use (a) and Total Economic Damages (b) Under the Law of the River.

actual drought damages during years 10 through 38 of the drought sequence.

Consumptive uses are generally satisfied in full during years 1 through 9. The single exception is consumptive use by southern California municipal users served by the Metropolitan Water District (MWD). At no time during the period are surplus conditions present in Lake Mead; as a result, deliveries to MWD are limited to senior rights only. The total shortfall to MWD gradually decreases from year 1 to year 9 as water made available from Imperial Irrigation District irrigation efficiency improvements and from the All-American canal lining project become available. By year 9 these projects are fully implemented, leaving a chronic shortfall to MWD of 636 kaf per year and resulting in damages estimated at $258 million annually.

Early Drought: Years 10 through 16

Basin inflows average only 11.8 maf per year during this initial phase of the drought. Basin storage is reduced from 50 maf in year 10 to 29 maf by year 16, with 87 percent of the storage loss occurring in the Upper Basin. Strikingly, active storage in Lake Powell is nearly exhausted (reduced to 4 maf, 15 percent of capacity) at the end of year 16. This loss of storage is a critical factor in shortfalls to Upper Basin users in subsequent years.

Consumptive Uses. Despite the dramatic loss of Upper Basin storage, the only shortfall to Basin consumptive uses remains the chronic shortfall to MWD. All other lower and Upper Basin depletions are satisfied in full.

Hydropower. With decreasing reservoir elevations and reduced flows, hydropower production falls throughout the period. The loss of hydropower heads results in a decrease from year 10 to year 16 in the marginal value of Upper Basin water for hydropower production. Total Basin hydropower production is reduced 29 percent by year 16 compared to base levels (Table 2).

Recreation. Damages to recreational users, primarily flatwater boaters at Upper Basin reservoirs, become significant by year 16 as Upper Basin storage is largely exhausted. Total Basin recreation benefits are reduced by 12 percent ($60 million) in year 16 relative to the base period, but these damages are unevenly distributed: benefits to boaters on Lake Powell are reduced 49 percent.

Salinity. Salinity concentrations slowly rise over the drought period as reduced flows concentrate salt loads. While reservoir storage buffers increases in any given year, a seven-year period of low flows results in both elevated river and reservoir salinity levels by year 16. Concentrations would likely exceed the Basin salinity standards adopted in 1976 of 723 mg/l below Hoover Dam and 879 mg/l below Imperial Dam. By year 16 damages to consumptive users from elevated salinity could exceed $300 million per year relative to the base level.

Critical Drought: Years 17-22

During the critical, severe period of the drought, Basin inflows average only 8.4 maf per year, never exceeding 10 maf in a given year. The Upper Basin is poorly prepared for these dramatic flow reductions, as

TABLE 2. Hydropower Production at Basin Reservoirs During Severe Sustained Drought Sequence (1992 dollars).

	Value of Power Generation (million $)			Marginal Value of Instream Flow ($/af)		
Hydropower Plant	Base Period	Year 16	Year 19	Base Period	Year 16	Year 19
Flaming Gorge	28	24	0	20.6	16.6	0
Curecanti Unit*	97	0	0	46.9	0	0
Navajo	32	0	0	17.7	0	0
Glen Canyon	239	172	0	27.1	20.9	0
Hoover Dam	204	210	197	24.7	24.0	23.0
Parker Dam	48	50	49	5.9	5.9	5.9
Davis Dam	24	24	24	3.4	3.4	3.4

*Composite of Morrow Point, Blue Mesa, and Crystal Dams.

storage was greatly reduced during the previous period of below normal flows. The Lower Basin retains significant storage to meet most of its requests for consumptive use. Instream uses are severely affected as very low flows occur and reservoir levels continue to decline.

Remaining Upper Basin active storage is exhausted in the first year of this critical phase. With insufficient inflows to satisfy consumptive users and meet the annual objective release of 8.23 maf from Glen Canyon Dam, Upper Basin uses are severely curtailed starting in year 18. In year 21, deliveries to CAP are reduced in a futile effort to protect power production at Lake Mead. By the end of year 22, storage in Lake Mead is nearly exhausted. Hydropower production is reduced to exceptionally low levels by year 21 as most power plants are rendered inactive by low reservoir levels. Table 3 summarizes drought damages to Basin consumptive users in year 21.

Consumptive Uses. Upper Basin consumptive uses lose up to 55 percent of requested depletions starting in year 18. Marginal damages are $630/af for thermal energy users with limited alternative supplies and $1,200/af for Colorado Front Range cities (e.g., Denver). Marginal damages suffered by agricultural users range from $58/af in Colorado for users with no alternative supplies to $23/af for New Mexico exports where Colorado River water is a supplemental supply source.

Lower Basin consumptive users are remarkably well protected from drought damages. CAP use is reduced by 665 kaf/year starting in year 21, a 60 percent reduction. Damages to CAP municipal uses (after inclusion of reduced CAP pumping costs) are estimated at $76 million annually starting in year 21. CAP agricultural users are also assumed to suffer reductions in CAP deliveries. From a national economic perspective, such reductions result in a net benefit of

TABLE 3. Consumptive Use Damages, Year 21 of the Severe Sustained Drought (1992 dollars).

Depletion Label	Consumptive Use (thousand af)	Proportion of Full Request)	Total Drought Damage ($ million)	Marginal Benefits ($/af)	Average Damages ($/af)
WYA1	51	0.49	1	37	21
WYA2	116	0.49	3	37	21
WYM2	55	0.49	16	483	271
UTA1	29	0.47	1	40	22
WYA3	53	0.49	1	37	21
COA1	45	0.41	2	59	26
COE1	18	0.41	8	640	311
UTA2	104	0.47	3	40	22
UTA3	248	0.47	6	40	22
UTE1	59	0.47	19	521	281
COA2	98	0.41	3	31	21
COM2	217	0.41	230	1234	727
COA3	218	0.41	8	59	26
COA4	206	0.41	8	59	26
COA5	91	0.41	4	59	26
COA6	118	0.41	5	59	26
AZUB	50	1.00	0	12	NA
NMA1	19	0.45	0	23	17
NMM1	31	0.45	32	1543	846
NMA2	63	0.45	4	47	46
NME1	41	0.45	14	545	288
NMA3	69	0.45	2	49	24
VNE1	11	0.47	4	521	281
NVM1	258	1.00	0	367	NA
CAM1	703	0.53	258	720	406
AZA1	153	0.25	–26	–53	–57
AZM1	297	0.59	72	549	349
AZA2	565	1.00	0	14	NA
CAA1	831	1.00	0	27	NA
CAA2	2840	1.00	0	27	NA
CAA3	394	1.00	0	27	NA
AZA3	715	1.00	0	20	NA

NA = Not Applicable.

$26 million annually because costs of pumping CAP water exceed the income produced by CAP agriculture.

Hydropower. By year 19, hydropower production is significantly reduced following the loss of the Flaming Gorge and Glen Canyon power plants to declining reservoir levels (Table 2). By year 21, Lake Mead also falls below the minimum power pool level necessary for power production, and total Basin production is reduced to only 10 percent of typical levels. The economic damage from lost production in the full Basin is estimated at just over $600 million annually.

Recreation. Damages to recreation users increase throughout the period as reservoir levels decline. The total loss of benefits relative to the base period reaches over $250 million by year 22 as most reservoirs are nearly depleted. Significantly, Lake Mohave and Lake Havasu maintain storage levels at capacity, preserving benefits to flatwater boaters of over $140 million in year 22.

Reduced instream flows decrease the value of whitewater rafting trips in the Basin. At the single site included in our model, the Grand Canyon, rafting benefits are reduced 75 percent to $2.4 million per year in year 21, as flows through the Grand Canyon are reduced from a typical 9 maf per year to only 2.5 maf/year. Grand Canyon fishing is less affected, with benefits reduced 30 percent to $0.4 million per year.

Salinity. Damages to consumptive users from salinity continue to increase as salinity levels rise throughout the critical drought phase. Levels up to 50 percent above the Basin salinity standards below Hoover and Imperial Dams are likely. Salinity levels in water delivered to Mexico would likely exceed 1400 mg/l. Damages to U.S. consumptive users could approach $500 million per year.

Recovery: Years 23-38

Basin inflows of 16.8 maf/year during the recovery period are almost exactly double those during the critical drought years 17 through 22. Reservoir storage levels are slowly rebuilt starting in year 23, while consumptive use returns quickly to near normal levels. With little high salinity water in storage, Basin salinity levels are also projected to return quickly to normal levels.

Consumptive Uses. With inflows exceeding 16 maf per year in years 23 through 28, Upper Basin use returns immediately to the full level of requested depletions while still allowing an annual release at Glen Canyon Dam of 8.23 maf, and additional water to rebuild storage levels. Additional Upper Basin releases to compensate the Lower Basin for reduced deliveries during the critical phase are not required by CRIM. Such releases might be required under the 1922 Compact, in which case damages to Upper Basin consumptive users would persist for several additional years. Diversions by CAP remain at low levels until year 28 due to low storage levels at Lake Mead.

Hydropower. Hydropower production returns to normal after 10 years of the recovery. The initial high flows do little to immediately restore production, however, as most plants remain inoperative due to low reservoir levels.

Recreation. Recreation benefits similarly return slowly to normal levels, with damages of nearly $200 million per year persisting for several years. Refilling of Basin reservoirs is the critical factor in returning flatwater recreation benefits to normal levels. With consumptive uses at high levels, reservoirs remain depleted for a number of years despite the higher than average inflows to the Basin.

Salinity. Basin salinity levels dramatically decrease in the first year of high flows. Because little (high salinity) water remains in storage, the dilution effects of the high flows are particularly strong. Further, depleted Basin reservoirs refill with low salinity water. By year 27, five years into the recovery, salinity concentrations return to levels typical of the base period.

Summary of Drought Impacts Under the Law of the River

A severe sustained drought of the type which might occur in the Colorado River Basin every 500 years would result in the following under the existing institutions allocating use of Basin water resources:

1. Exhaust virtually all Upper Basin water storage.
2. Greatly reduce hydropower production at Upper Basin power plants and reduce opportunities for Upper Basin flatwater recreation. Total impact: nearly $500 million in direct economic damages annually for up to seven years.
3. Leave Upper Basin consumptive users vulnerable to severe supply shortfalls. Such shortfalls could result in direct economic damages of $400 million annually for several years.
4. Potentially deplete Lower Basin storage, with further hydropower and recreation losses of $300 million annually for up to six years.

5. Result in salinity levels in Lower Basin drinking and irrigation water significantly above any experienced since construction of Hoover Dam, and which exceed existing Colorado River standards.

Sensitivity to Model Assumptions

A large number of specific assumptions are necessary in a modeling effort of this scale. Some assumptions may directly affect model results, while others may be relatively innocuous. The sensitivity of the results presented in the previous section to several specific model assumptions are discussed here.

Choice of Model. Three modeling systems were utilized in the study of the severe sustained drought reported in this issue. While each model provided particular advantages, consistent predictions of the effect of a severe sustained drought on the Basin were found across models. For example, Figure 2 compares reservoir storage when the CRIM and CRM models (Harding *et al.*, 1995) use identical depletion data. The CRIM model is particularly useful for comparing the performance of alternative policy responses to drought. Because CRIM is a partial equilibrium model, its direct damage estimates should be treated with caution. More importantly, uncertainty in the underlying benefit functions for various uses, particularly at large reductions from full supply levels (e.g., ≥ 50 percent) where damages are not well understood implies that CRIM damage estimates should be treated as provisional.

Drought Definition. The drought utilized in this study is precisely defined by a 38-year hydrologic inflow sequence, together with initial reservoir conditions. One major result is the virtual emptying of Upper and Lower Basin reservoirs. Upper Basin reservoirs are depleted first, followed by the drawdown of Lake Mead. Hydropower and recreation losses occur throughout the period of lowered reservoir levels, while consumptive use shortfalls are limited to the period (and immediate aftermath) of extremely low flows. The precise magnitude and timing of hydropower and recreation damages are sensitive to the inflow levels used in the drought sequence, and to reservoir initial conditions. Upper Basin hydropower and recreation damages discussed above would occur even with initial storage at capacity given this study's drought sequence. Similarly, damages of similar magnitude would occur if our initial reservoir conditions and a somewhat less severe though similarly sustained drought sequence were used. One robust conclusion is that the first and inevitable drought impact under the Law of the River is a reduction in Upper Basin storage.

The duration of consumptive use shortfalls (and to a lesser extent their magnitude) and the minimum Lower Basin reservoir levels reached during the drought are highly sensitive to the precise drought inflows and initial reservoir storage. The sequence of low flows is less important, though reductions in Upper Basin use when Upper Basin storage is exhausted are greatly reduced as inflows approach normal levels.

Consumptive Use Levels. Just as small changes to inflow levels impact consumptive use shortfalls, such shortfalls are highly sensitive to total consumptive use levels. For example, if actual Upper Basin consumptive use were just 10 percent below that given by our depletion request data, Upper Basin shortfalls would be delayed by two to three years, and the total period of critical shortfalls would be reduced from five years to perhaps two years. Economic damage estimates assume that consumptive use shortfalls within Upper Basin states occur across all uses. To the extent that this does not hold and higher valued uses have relatively senior (junior) rights, drought damages are overstated (understated).

Salinity. Modeling Basin salt levels includes numerous uncertainties. Quantitative estimates of future salinity levels under drought may contain large errors. Water stored in Basin water clearly buffers salinity increases during low inflow periods and would tend to slow reductions in salinity levels during high inflow periods. In the extended drought presented here, little stored water remains when high inflows return to the Basin. The estimated rapid recovery from high salinity levels is a direct consequence of such low storage levels; if minimum storage levels were in fact greater, high Basin salinity concentrations would persist over a longer time period. Salt inflows during periods of greatly varying water inflows are not well understood. Further, salt loading from human sources when consumptive use is temporarily reduced is difficult to estimate Basinwide. These uncertainties suggest that Basin salinity estimates should be treated with extreme caution.

One approach to estimating salinity levels when storage is virtually exhausted is to review historical salinity records prior to the closing of Glen Canyon Dam. Such records (U.S. Department of Interior, 1989) suggest that large annual fluctuations in levels would occur, with peak monthly concentrations reaching 1,400 mg/l at Lees Ferry. Because inflows during the most critical years of our study drought are significantly below the historical conditions during which peak salinity concentrations were measured, river salinity concentrations greater than 1,400 mg/l would be likely.

Economic Valuation. Drought damage estimates rely on model estimates of physical impacts (e.g., consumptive use reductions or loss of hydropower production) together with valuation estimates. The sensitivity of physical impacts to alternative model assumptions is discussed above. Increases or decreases in the estimated marginal value of water uses at full deliveries would result in similar proportional increases or decreases in damage estimates. For example, if Lower Basin hydroelectric power were valued 50 percent above the estimate of 47 mills/kwh (Booker and Colby, 1995) used here, then damages to Lower Basin hydropower users would be 50 percent greater than reported. Increases or decreases in assumed price elasticities of demand could generate much greater differences in estimated damages. Similarly, drought damage estimates are highly sensitive to the availability of non-Colorado River supplies.

DESCRIPTION AND IMPACTS OF ALTERNATIVE POLICY RESPONSES

Damages which result from drought are dependent on the particular water management policies in place during all phases of the drought. The impacts reported above under the existing Law of the River assume static policies throughout the severe sustained drought. This is unrealistic. While the particular policies which would be adopted under such conditions are unknown, a major purpose of this study is to report on the impacts of alternative policies which could plausibly be adopted. We introduce first a number of specific policies which have been proposed as responses to water shortfalls in the Basin. Some policies are potentially complementary: adoption of one would not exclude adoption of a second policy. Others are mutually exclusive and could not be simultaneously implemented. No single ideal policy is identified. Some of the proposed policies were found to be effective in reducing drought impacts, while others (sometimes surprisingly) have little effect or increase damages.

Policy responses to drought can be grouped into three categories based on the general approach: river management, legal environments, and market based. Within each category both state and regional responses may be possible. The specific individual policies investigated for this study are briefly described below, together with a summary of drought damages under each policy response. The objective function used in CRIM remains Equation (1) unless otherwise stated.

River Management Responses

Ten-year Average Delivery at Lees Ferry. Existing operating rules set by the Secretary of the Interior require an "annual objective release" from Glen Canyon Dam of 8.23 maf to satisfy Upper Basin obligations under the Colorado River Compact. During periods of low flows, this required release inevitably leads to the drawdown of Lake Powell, though Lake Mead storage may remain close to capacity. A fixed annual release is not required under the Compact (MacDonnell *et al.*, 1995) and may thus lead to Upper Basin shortfalls during a sustained drought which might otherwise not occur. The requirement for a fixed annual release is changed to a 10-year delivery requirement of 75 maf, consistent with the Compact, plus an additional 7.5 maf per 10 years to satisfy the Upper Basin's Mexican delivery obligation. Equalization of storage in Mead and Powell is also added as a priority when it does not conflict with Compact deliveries. Note that the previous equalization rule could only cause releases from Powell to increase storage in Mead. The changes are implemented for the full 38-year drought sequence.

The impact of these two changes is to allow releases from Powell in a given year of less than 8.23 maf, thus preserving Upper Basin storage when it is below Lower Basin levels. Figure 4 shows this effect starting in year 7; it is important through year 12. After year 12, these lower than normal deliveries must be "paid back," however. This occurs in years 13-17. In years 18-26 the Compact is not satisfied: 10-year average deliveries fall below 8.23 maf/year.

Impacts under this policy response demonstrate an important result: the annual objective release of 8.23 maf does not cause the draining of Lake Powell. Rather, a failure (perhaps inevitable) to reduce Upper Basin use during moderate drought conditions causes the loss of storage. Damage to Upper Basin users inevitably follows when the drought does not end, and the senior rights of the Lower Basin must be satisfied. Indeed, forcing the annual objective release results in a quicker recovery from drought (year 23 of the base policy, though the Lower Basin could argue that the Compact is violated in this case by not requiring higher deliveries) than would this representation of the Compact (where Upper Basin use does not return to full levels until year 26.) Hydropower production is somewhat higher with this policy as reservoir levels are generally slightly higher; this result does not hold in all years, however.

Given a Lower Basin senior right of 7.5 maf/year, plus senior deliveries to Mexico, a loss of all but "present perfected rights" (rights prior to the 1922 Compact) for several years is inevitable in the Upper

Basin. The details of how the Compact is implemented are not particularly important. Only preemptive reductions in Upper Basin use as Powell is depleted would be helpful. Given the severity of the drought, however, no likely policy of early reductions in use could prevent the draining of Powell and hence severe reductions in Upper Basin use.

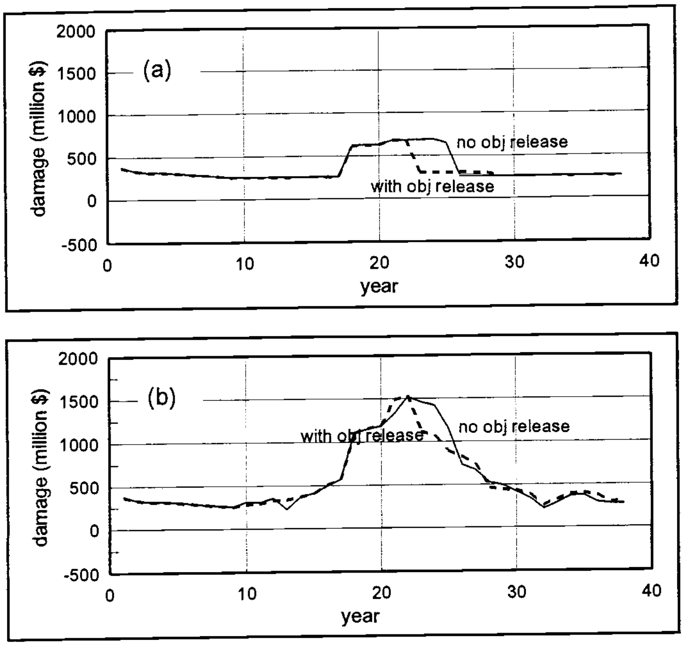

Figure 4. Consumptive Use (a) and Total Economic Damages (Excluding Salinity) (b) with a Ten-year Average Delivery Requirement at Lees Ferry (i.e., no annual objective release).

Basin Reservoir Management. Evaporation losses at Basin reservoirs vary dramatically. Evaporation from mountain reservoirs is little over 1 foot/year, while that from Lake Havasu exceeds 6 feet/year. Because existing reservoir management favors storage at Lower Basin locations, reductions in evaporation losses should be possible through changes in management rules to emphasize storage in Upper Basin locations. Specifically, under this "store high" response, water is preferentially stored at high-elevation reservoirs. Managing Basin reservoirs using this rule would require suspending Compact-related delivery requirements at Lees Ferry. Compact allocations, however, could be maintained through appropriate accounting rules tracking storage for Upper and Lower Basin use, regardless of storage location. The change is implemented for the full 38-year drought sequence.

Reducing evaporation losses through preferential storage in Upper Basin reservoirs eliminates most drought-induced shortfalls to consumptive users (Figure 5). The small annual savings achieved by this policy occurring over the many years of the drought sequence result in several additional years of drought protection. Significant supply shortfalls would occur, however, were the critical phase of the study drought to extend even a single additional year, as total Basin storage falls to 2.3 maf in the final low flow year. The policy is thus highly effective at achieving small annual savings, resulting in a significant increase in the consumptive use drought protection provided by Basin reservoirs. Total damages across all uses (Figure 5) are not as effectively reduced as are consumptive use damages. In all but the critical drought years, total damages under this policy are greater than under the Law of the River, largely because of recreation and hydropower losses as Lower Basin reservoir levels are drawn down. These could be largely mitigated (in non-critical years) by maintaining storage near capacity in Lakes Mohave and Havasu, while limiting Lake Mead drawdown to maintain hydropower production. Such a hybrid policy was not modeled in this study.

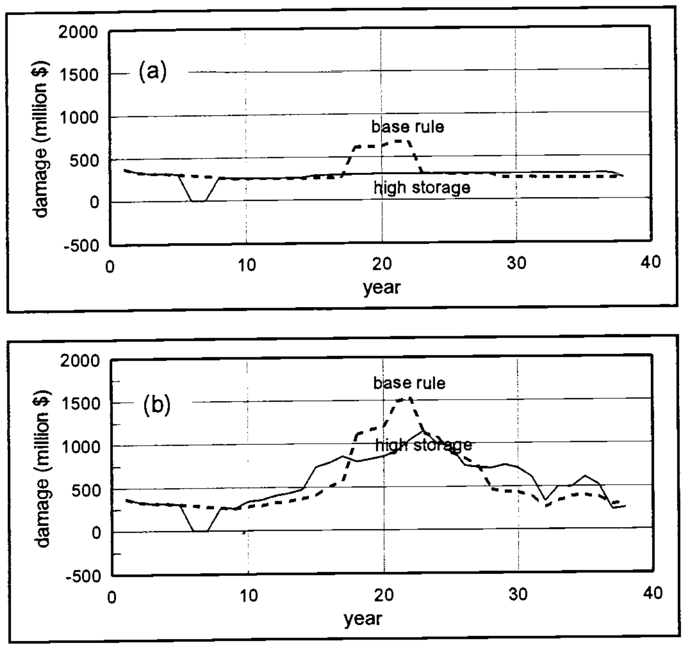

Figure 5. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with "Store High" Management of Basin Reservoirs.

Storage for Hydropower Generation. Large losses in hydropower generation result from the severe flow reductions occurring under a severe drought. When the drought is a sustained event and reservoirs are drawn down below minimum power pool levels, hydropower production ceases. Such extreme depletion of reservoir storage occurs under existing reservoir management in the severe sustained drought studied here. Some hydropower generation could be maintained by limiting drawdown of each reservoir to the minimum power pool level. One consequence of such a rule would be a further reduction in consumptive uses, however. A constraint limiting drawdown to minimum power pool is added for the full 38-year drought sequence. An exceptional drawdown to 2 maf below minimum power pool is allowed at Lake Mead when total Basin inflows are less than approximately 8 maf and storage is already at minimum power pool.

Management to maintain minimum power pool levels more than doubled damages to consumptive users during two years of the critical drought phase, with some increased damages occurring over a ten-year period (Figure 6). Small increases in hydropower production over the base policy were found, but large hydropower (and recreation) damages were not avoided (Figure 6). Minimum power pools could not be maintained during several drought years, while the very low flows available during years 17-22 further limited hydropower production. This simple policy was not effective in reducing total drought damages.

Changes to Legal Environments

Proportional Sharing of Shortfalls. Restrictions on water use during shortfalls are presently based on priority systems: intrastate allocations are based on seniority, while the Lower Basin states taken together enjoy highest priority for the great majority of their use of Basin water. The consequence of such systems is uneven patterns of shortfalls. This result is the basis for one major criticism of priority systems. Individual users within states and the Upper Basin states taken together may experience severe shortfalls while others may be fully protected from consequences of drought. The exception to this rule is the proportional sharing of Upper Basin water shortfalls among the Upper Basin states of Colorado, New Mexico, Utah, and Wyoming. Following this example, shortfalls to Colorado River Basin consumptive users in a particular year are distributed among all users. This rule is applied in years where the total shortfall exceeds 1 maf.

Consumptive use damages from drought shortfalls were significantly reduced when shortfalls were proportionally imposed across all uses (Figure 7). Drought damages during years 17 through 22 were reduced to roughly 50 percent of levels estimated under the base policy. This significant reduction in damages occurred because municipal and industrial (M&I) users were better protected from drought than under the base policy. Benefits to M&I users significantly outweighed additional damages to agricultural users. Additional impacts to nonconsumptive users were minimal (Figure 7).

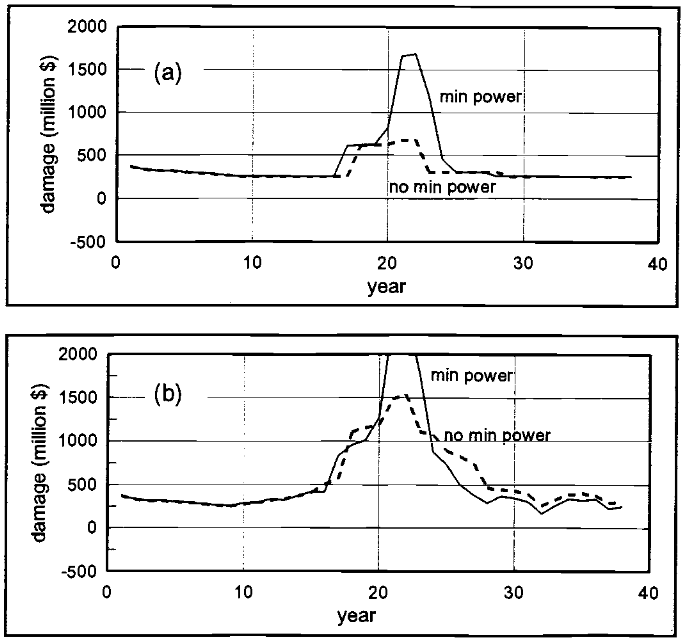

Figure 6. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Maintenance of Minimum Power Pools for Hydropower Generation.

Shifting Shortfalls to Agricultural Sectors. Many believe that water shortfalls are more economically damaging to M&I users than to agricultural users. If this is indeed the case, minimizing drought damages would require some shifting of shortfalls from M&I users to agricultural users. Following this logic and presuming that proportional reductions to agricultural users minimize drought damages, a change to legal rights which protect M&I users from drought while imposing proportional shortfalls on agricultural users is followed. The rule is applied in years where the total shortfall exceeds 1 maf.

If consumptive use shortfalls are shifted entirely to agricultural users (and distributed proportionally between such users), total consumptive use damages in years 17 through 22 are reduced by up to 85 percent (Figure 8). Further, such a policy would

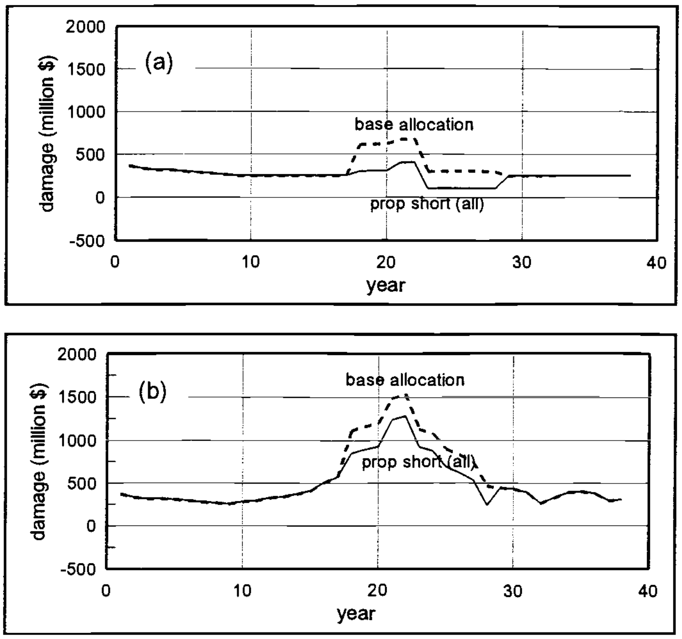

Figure 7. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Proportional Sharing of Shortfalls by All Users.

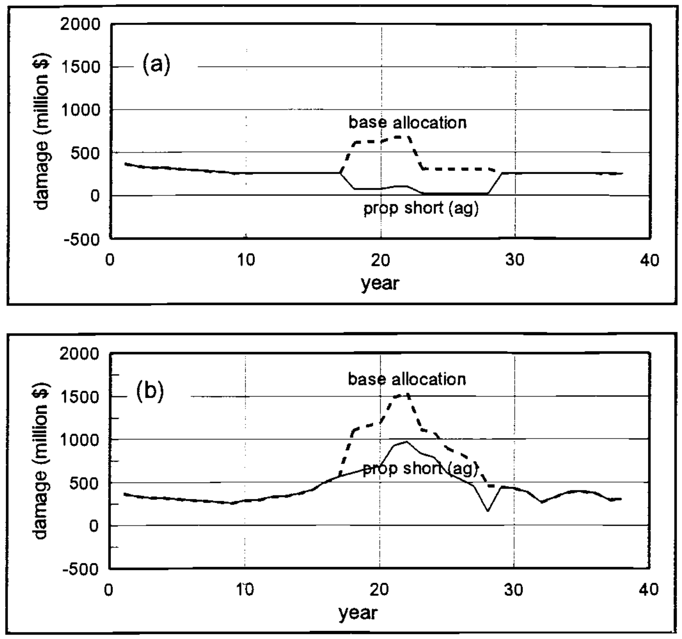

Figure 8. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Shortfalls Shifted to Agricultural Users.

greatly reduce damages from the chronic shortfall to MWD users (see years 21 through 28 where the policy remains in place.) Nonconsumptive use damages are largely unaffected by the policy (Figure 8). For limiting total Basin damages to consumptive users, however, this is a highly effective policy.

Market Based Policy Responses

Intrastate Water Banks. Results from gaming simulations (Henderson and Lord, 1995) suggest that state-level responses can be important in mitigating drought impacts. One approach is to reallocate state water allocations based on intrastate consumptive use values, using state water banks, or direct marketing of water rights between users. Water users are also required to pay full water delivery costs under this policy. Such policies can be implemented unilaterally by states. Intrastate water bank allocations are applied in all years using a second optimization in each time step (see Equation 5 below), with state allocation constrained to those determined by the Law of the River.

Short-term intrastate markets could reduce consumptive use damages in years 17 through 22 by up to 85 percent relative to damages under the base policy (Figure 9). Chronic damages to MWD uses would also be reduced through marketing by California agricultural users. CAP agricultural users would be unable to pay for pumping of CAP water; the result is a net benefit from the national economic perspective. Nonconsumptive use damages are largely unaffected by the policy (Figure 9). For limiting total Basin damages to consumptive users, this is a highly effective policy.

Interstate Consumptive Use Water Bank. Additional benefits from water marketing may remain if state-level transfers do not bring about similarly valued water uses across Basin states. If marginal values in consumptive uses differ greatly, then additional benefits from interstate water marketing are likely. An interstate consumptive use water bank is applied in years where the total shortfall to Basin users exceeds 1 maf. A water bank is simulated by allocating Basin water to maximize consumptive use benefits in each year. The CRIM objective function becomes in this case

$$V = \sum_{p} \left(V_p(x') - C_p(x') \right) \tag{5}$$

where $V_p(x')$ is the total benefit from use of Basin water x' at point p and $C_p(x')$ is the total conveyance and treatment cost at point p.

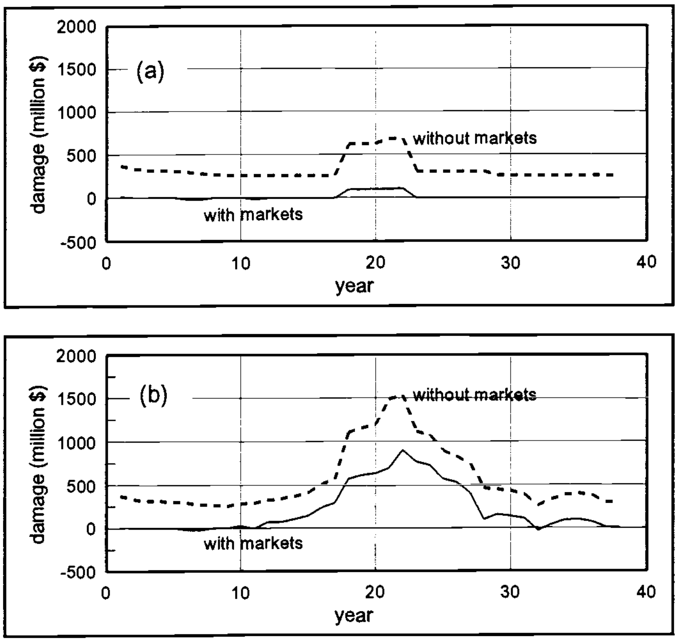

Figure 9. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Intrastate Water Banks (Markets).

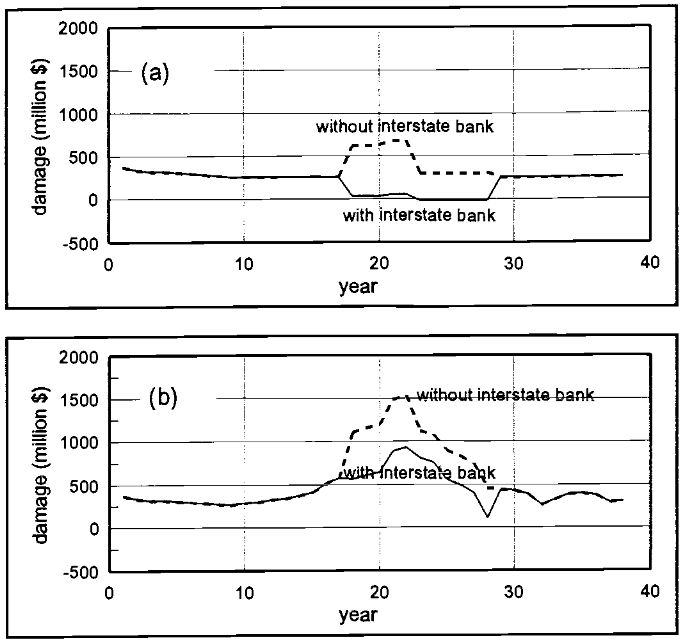

Figure 10. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with an Interstate Consumptive Use Water Bank.

An interstate water bank would reduce drought damages to consumptive uses by 85 percent during years 17 through 22, reduce chronic damages to MWD uses, and eliminate CAP agricultural uses (Figure 10). Reductions in consumptive use damages are minor beyond those achievable with intrastate markets or a policy shifting shortfalls to agricultural users. During critical drought years damages to nonconsumptive users increase slightly from those estimated under the base policy (Figure 10) as water is transferred to Upper Basin consumptive uses, further decreasing the remaining hydropower production.

Comparison of Policy Responses

Effective policy responses to drought must address shortfalls to consumptive users and damages from lost hydropower production and recreational opportunities. Salinity damages can also be addressed through policy responses but are not formally treated here [see Booker and Young (1994) for economic impacts of alternative approaches to balancing consumptive and nonconsumptive use benefits, including salinity damages].

Figure 11 summarizes the discounted total damages for years 17 through 28 under the policy responses presented above. The time period chosen is that during which consumptive use shortfalls greater than the chronic MWD shortfall were found under the base Law of the River policy simulation. Nonconsumptive use damages were also greatest in this period. Under the Law of the River policy, the present value of total damages for the 12-year period discounted at a 4 percent annual rate to year 17 is $9.5 billion; if discounted to year 1, the present value of damages is a factor of two less, or roughly $5 billion. The latter figure provides an estimate (in 1992 dollars) of the present value of drought damages (excluding salinity damages) for the 12 years of greatest drought impact, were the full drought sequence to begin this year.

Consumptive use damages (making up 45 percent of the total damages) can be largely mitigated through reallocations from low (primarily agricultural) to high (municipal and industrial) valued uses. Reallocations could occur through changes in legal priorities during drought (the policy shifting shortfalls to agricultural sectors) or through water marketing (e.g., intra- and interstate water banking). Policies providing small annual increases in available supplies (e.g., the "store high" policy to reduce evaporation losses) or those which distribute shortfalls between all users (e.g., the proportional sharing of shortfalls policy) are somewhat effective in reducing total consumptive use damages.

Damages to hydropower production and recreational uses are typically both greater in magnitude than consumptive use damages and more difficult to reduce through policy measures. Maintenance of minimum

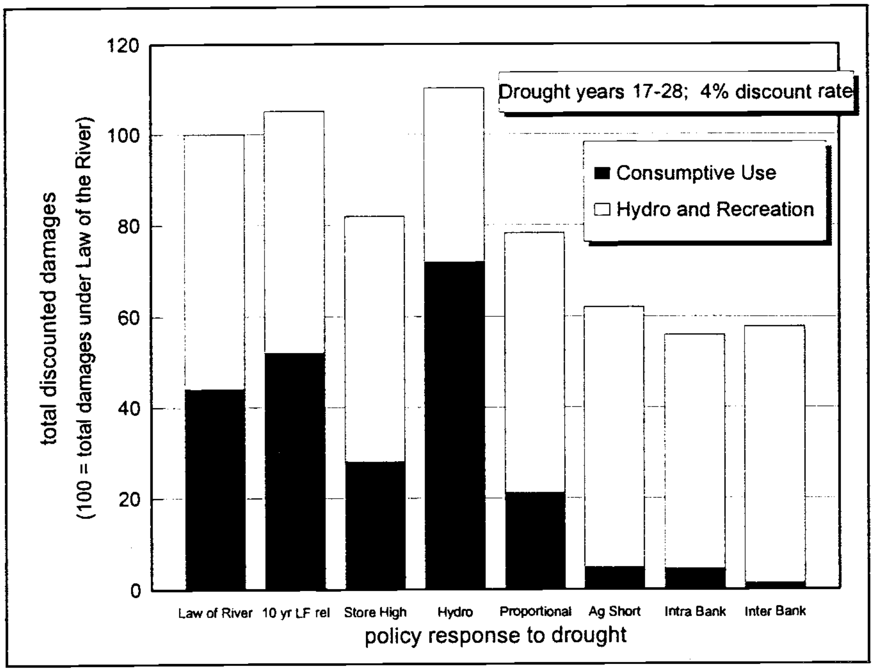

Figure 11. Present Value of Total Drought Damages (excluding salinity) for Years 17 through 28. Were the full drought sequence to begin this year, the present value of Law of the River damages would be $5 billion (1992 dollars).

reservoir levels (primarily for hydropower production but also resulting in recreation benefits) is most effective at reducing such nonconsumptive use damages (31 percent reduction). Damages from large increases in consumptive use shortfalls outweigh these nonconsumptive use benefits, however. Other policies have little effect on nonconsumptive use damages, ranging from an 8 percent reduction (intrastate water banking), to 1 percent to 2 percent increases with proportional distribution of shortfalls and interstate banking.

The modeled shortfall of 636 kaf/year to MWD users obscures damages to other users arising directly from the drought. It is likely that these chronic shortfalls to MWD will be reduced through future transfers from California agricultural users in the Imperial and Palo Verde Irrigation Districts not reflected in the depletion request data used for this study. Focusing only on the purely drought-related damages stresses the significance of nonconsumptive use damages: under the base Law of the River policy, such damages are fully 72 percent of drought-related damages, with consumptive use damages only 28 percent of the total.

Policy Recommendations

Four policy responses are nearly equally effective at reducing drought-related damages. Intra- and interstate water banking reduces such damages by 28 percent and 26 percent, respectively. Shifting consumptive use shortfalls to agricultural users reduces damages by 20 percent, while managing Basin reservoirs to reduce evaporation losses (the "store high" policy) reduces damages by 23 percent. The latter two modeled policies maintain subsidized agricultural uses of CAP water, accounting for the major difference in damages relative to the water-marketing policies which eliminate such use. These results strongly suggest that most gains from water reallocation during drought are possible through intrastate policies. Further, because most agricultural regions include a large proportion of low-valued crops, simple across-the-board reallocations from agricultural to municipal uses during drought is a nearly economically efficient policy. Increasing available supplies through reservoir management is an independent policy with a significant impact in reducing drought damages. Reducing damages to hydropower production and recreation imposes increased consumptive use damages (hydropower protection policy). These increased damages could be greatly reduced, however, through use of one of the four policies identified above.

Together, three policy responses are suggested to reduce damages from drought in the Colorado River Basin:

1. Reallocation from low-valued to high-valued consumptive uses when shortfalls occur.
2. Reservoir management to reduce evaporation losses and increase available supplies.
3. Increased emphasis on maintenance of minimum reservoir levels to support hydropower production and recreational opportunities.

Policies (1) and (2) independently reduce total damages and thus need not be linked. Policy (3) reduces total damages only if a reallocation policy for reducing consumptive-use impacts (1) is also applied. Utilizing all three policy responses together would result in the greatest total reduction in damages from a severe and sustained drought.

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A GAMING EVALUATION OF COLORADO RIVER DROUGHT MANAGEMENT INSTITUTIONAL OPTIONS[1]

James L. Henderson and William B. Lord[2]

ABSTRACT: Researchers representing each of the Colorado River Basin states as well as the Secretary of the Interior were presented with an interactive computer simulation of a progressively increasing drought and were given the collective opportunity to change the ways in which basin-wide and within-state water management were conducted. The purpose of this "gaming" exercise was to identify rules for managing the Colorado River which are effective in preventing drought-caused damages to basin water users. This water management game was conducted three times, varying the collective choice rules for management of the river yet staying substantially within the current institution for management of the Colorado River known as the "Law of the River." The Law of the River was quite effective in minimizing drought impacts upon consumptive water uses. Additional effective drought-coping measures to protect consumptive uses consisted mostly of intrastate water management improvements which states were able to implement independently. The Law of the River did not protect non-consumptive water uses, such as hydroelectric power generation, water-based recreation, endangered species, and water quality from drought, as well as it protected consumptive water uses. Players reached collective choice decisions to cope with rising salinity, equalize storage between the upper and lower basins, and protect endangered species. While these measures had some success, only reductions in withdrawals for consumptive uses, particularly in the upper basin, could have substantially lessened adverse impacts.
(KEY TERMS: institutions; gaming; drought; simulation; water management; water policy; Colorado River Basin.)

INTRODUCTION

Institutional analysts often distinguish three different levels of decision making and action in any public choice situation. They are the operational, collective, and constitutional choice levels (Ostrom, 1986). Action which occurs at each of these levels does so subject to rules which govern the behavior of participants. Such rules also are designated as operational, collective, and constitutional choice rules.

Resource allocation and management occurs at the operational choice level. In the case of a severe sustained drought in the Colorado River Basin, the relevant actions are those of the seven basin states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) and the federal government in operating the water storage and diversion facilities, and this makes the Colorado River the most highly regulated river in the world. Such actions are taken pursuant the operational choice rules, which in this case have come to be known as the "Law of the River." Examples of parts of the Law of the River that have spawned operational choice rules are the Upper Colorado River Basin Compact of 1948 and the Colorado River Compact of 1922, the Endangered Species Act and the Clean Water Act, the 1964 Supreme Court decree in Arizona vs. California, and the operating criteria established for the operation of Glen Canyon and Hoover Dams, which are followed by the Department of the Interior.

Operational choice rules are made and changed at the next higher level of decision making, the collective choice level. Action at this level is concerned only with the making of operational choice rules. Examples of actions taken at the collective choice level include the formulation by the seven states of the Colorado River Compact in 1922, Congressional passage in 1928 of the Boulder Canyon Project Act, and the Supreme Court decision in 1963 in Arizona v. California. These actions have been taken pursuant to collective choice rules which determine how the process of interdependent decision making about rules must be conducted. Collective choice rule changes are made within the framework of the next higher level of decision, the constitutional choice level. Constitutional choice rules

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include rules established by the U.S. Constitution, court interpretations, and procedural rules of Congress and the executive branch.

Gaming is one tool used in order to simulate the process of changing operational choice rules. Gaming is the technique of placing subjects in an environment which requires them to make joint or collective decisions among hypothetical options, the prospective consequences of which are shown to them as their interaction proceeds. Repeated "plays" of these games, under differing scenarios, allow subjects to explore the likely impacts or consequences of their collective options by playing "what if?" games. Studies have shown that it is usually possible to discover options which can perform substantially better than existing operating rules in coping with drought or other system-wide problems (Sheer *et. al.,* 1989). Gaming participants can evaluate their alternatives at far less cost, whether in time, money, or other resources, by gaming than by trying out these options in a real setting. Furthermore, repeated trials enable otherwise irreversible mistakes to be discovered within the gaming environment and avoided outside of it.

When conducting gaming exercises, players can carefully specify the collective decision rules in order to allow evaluation of current or proposed institutions. It is then possible to see which of these collective choice rule sets leads to the adoption and implementation of the "best" sets of operating rules (as measured by the consequences of adopting and implementing them). In this way, gaming can be used to discover superior rule sets (institutions) at *both* the operating and collective choice levels.

In this study, three combinations of collective choice decision rules and information availability conditions, each corresponding to the current and two proposed forms of the Law of the River, were used to conduct a gaming exercise for management of the Colorado River. Two different types of operational rule changes were allowed. Intrastate operational rule changes were used to simulate independent decisions made within each state to manage Colorado River water. Interstate operational rules were used to identify actions that states could take collectively to manage the river. The gaming exercise was then conducted using an interactive computer model to identify superior sets of operational level rules for management of the Colorado River in the event of a severe sustained drought.

METHOD

We constructed a drought game by modeling the hydrology, water management facilities, institutions, and economies of the Colorado River Basin by using an interactive simulation modeling tool (STELLA II, tm High Performance Systems, Inc.). The resulting model, called AZCOL, was used to simulate a severe sustained drought and to offer gaming participants the opportunity to manage this hypothetical drought, as it unfolded before them, by changing the operating rules for the system.

The AZCOL model of the Colorado River Basin was constructed specifically to facilitate the gaming exercise, and it relies heavily upon models and methods developed by others on the Severe Sustained Drought (SSD) research team. Representation of basin hydrology, of management facilities, and of current operating rules follows The Colorado River Model (Harding, 1994), while estimation of benefits from Colorado River water use and salinity damages is based upon CRIM (Booker, 1994). Environmental impact indicators were developed by Hardy (1994).

AZCOL is an annual model of the basic hydrology of the basin, with twelve withdrawal points, at least one for each of the seven states which use Colorado River water. Allocation of the river is governed by the operating rules for storage and delivery of water. The priorities and operating criteria which make up these rules are incorporated into AZCOL by using basic logic statements to govern reservoir operations and withdrawal. AZCOL also models salinity throughout the basin, evaluates the dollar benefits from the use of Colorado River water in each state along with hydropower and recreational benefits, and provides general indicators of the condition of environmental resource elements, such as threatened and endangered species (for a more complete description of AZCOL, see Appendix I of Lord *et. al,* 1994).

The drought employed for the games was the most severe sustained drought which tree ring researchers have been able to reconstruct from historic data. The same drought sequence was run in each of the three games in order to maintain the consistency in severity of drought across games and comparability between games [see Tarboton (1995) and Harding *et. al.* (1995), for details on the drought used and its construction from tree ring records].

The participants played the roles of the seven basin states and the federal government. Each player was a member of the SSD research team. All participants were water resource specialists with detailed knowledge of Colorado River Basin management. In addition, players were assigned to play for a particular state because they had specialized knowledge of the Colorado River management philosophy of that state as well as of the physical Colorado River conditions pertinent to that state. A total of 11 players played the seven states and the Secretary of the Interior (SOI) over the three games. Changes in players were necessary over the three games because of the length of the games and scheduling conflicts.

Each game was run by allowing pauses in the drought simulation during which players were allowed to make intrastate management decisions and propose and vote on interstate management proposals. Decisions and proposals were allowed in simulation years that were a multiple of five or when the drought reached a major change in system condition. These changes in system condition were called "trigger points" and corresponded to the following water availability conditions on the river: declaration of surplus in the lower basin, shortage in the upper basin, three possible stages of shortage in the lower basin, and a condition where none of the above are true, termed "normal." (For further definition and discussion of the trigger points, see Appendix I.)

Drought impacts were displayed to participants using 1-2 page reports with information for the period of time since the previous decision point in the game. Each player received an individual report containing information pertinent to that particular player's role in the game, as well as a general report with information about basin-wide conditions.

Prior to the gaming, we conducted interviews with what we then believed would be the players in order to elicit their interpretation of the value judgments they believed to be consistent with the water management objectives of states for which they would play. We used the MATS computer program (Brown *et. al.*, 1986), developed by the Bureau of Reclamation, to do this. MATS is only one of a number of techniques (ELECTRE and MAUT being others) designed to help decision makers understand their own values and the implications of those values for decision making. In essence, we asked these subjects to trade off economic, environmental, and equity values. We found that, in general, players rated economic impacts as more important than either equity or environmental preservation. However, the value elicitation for the SSD gaming was limited to seven subjects, only six of whom participated in the gaming, leaving five of the participants unrepresented. Therefore, we do not wish to make too much of these results.

More fundamentally, it was not our purpose to impose any set of evaluative criteria upon the decisions made by the subjects. Instead, we attempted to determine what changes in rules for water management they might be able to make in the face of an extreme event, under each of three collective choice rule sets. Such changes, if any, might be good or bad from any of a variety of perspectives. In our conclusions and recommendations, we attempt to critique those decisions from what we believe to be a broadly representative value set, but since eliciting that value set was not a part of our research, our critique is, accordingly, qualified.

COLLECTIVE CHOICE RULES

The drought game was played three times, the first time under collective choice rules which correspond to those currently in place, the second time under rules such as those which might characterize an interstate river basin commission, and the third time under rules which permitted water marketing between states. Under the first rule set, modification of the current ways of managing the system required unanimous agreement of all of the basin states and of the Secretary of the Interior, although each of the seven states could make independent decisions about how to manage water within its boundaries. Each of the states operated with whatever information was peculiar to it, together with a limited set of hydrologic information produced by the federal government and made available to all states. This game was played by electronic mail, thus facilitating participation by a geographically disperse group of players and preventing the players from conducting face-to-face and possibly bilateral negotiations.

The interstate compact commission was assumed to produce a broader array of information and to distribute it to all of the member entities so that the information rules changed substantially for the second play, but the aggregation rule of unanimity did not change. The players were assembled in a single location, and the information produced was essentially available to all.

The third play of the game was characterized by these same broadened information rules, but the aggregation rules were changed to permit any two states to decide to lease or sell water between them, although the Secretary of the Interior retained a veto power in order to prevent material injury to third parties. The collective choice rule for interstate operational rule changes not related to water marketing remained in unanimous agreement in the third game. The players were again assembled in the same location. Table 1 summarizes the collective choice rules, plus the operational level rules discussed next.

OPERATIONAL RULES

Participants in the SSD gaming exercises could choose from two different types of operating rules. They were *intrastate* and *interstate* rule sets. Participants representing any of the seven basin states could

TABLE 1. Summary of Collective Choice Rules and Operational Level Rules.

Collective Choice Rules

Game	Information Availability	Collective Choice Rule
1. Existing Conditions	Limited	Unanimity
2. River Basin Commission	Extensive	Unanimity
3. Interstate Water Marketing and Water Banking	Extensive	Bilateral Agreement for Interstate Choices 9 and 10, Unanimity for Interstate Choices 1-8

Operational Level Rules

Intrastate Choices - All States Except Arizona

1. Strict prior appropriation
2. Proportional sharing of water scarcity between agricultural and non-agricultural uses
3. Intrastate water marketing

Intrastate Choices - Arizona (all options include strict enforcement of the Arizona Groundwater Management Act)

1. No subsidy to agricultural users with CAP contracts
2. Subsidy for irrigators with CAP contracts to lower the price of CAP water to that of ground water
3. No subsidy to agricultural users
   Extensive recharge of CAP water into Arizona aquifers

Interstate Choices

1. Uncompensated shorting of Mexican delivery obligation
2. Compensated shorting of Mexican delivery obligation
3. Revision of operating criteria for Hoover Dam
4. Revision of operating criteria for Glen Canyon Dam
5. Modification of upper basin reservoir operating rules which attempt to maximize power generation at Glen Canyon Dam in the event of a drought
6. Modification of all reservoir operating rules to meet the requirements of the Endangered Species Act
7. Implementation of a salinity control program which includes on-farm water-use efficiency improvements and/or control of natural source salt loading, in addition to those programs already in place
8. Activation of the desalinization plant at Yuma, Arizona to reduce salinity of water delivered to Mexico in compliance with Minute 242 of the International Boundary and Water Commission agreement with Mexico
9. Interstate water marketing (allowed only in game three)
10. Interstate water banking (allowed only in game three)

select from the intrastate options menu unilaterally (without consulting or informing other participants). In other words, they were free to manage water appropriated to their individual states without interacting with other states. Interstate water allocation options could be adopted and implemented only through a collective choice process involving other participants. Individual state participants could propose changes in the interstate water allocation rules, but they could not adopt, much less implement, such changes unilaterally.

Intrastate Operating Rule Options

There were three possible intrastate operating rule sets available to each state participant. In all states except Arizona, these options were as follows:

1. Strict prior appropriation, under which available water supplies were delivered to holders of water rights solely according to the seniority of their rights. This was interpreted to mean that agricultural water rights, being generally senior, would be satisfied first. Shortages fall mainly upon municipal users. This option implemented appropriation doctrine but also assumed that water transfers would not occur as a response to scarcity (in reality, the barriers to free transfer of appropriative rights vary significantly among the basin states).

2. Proportional sharing of water scarcity, under which water use cutbacks are imposed upon all water users, without regard to seniority, in the event of supply shortages. This was interpreted to mean that each water use would be shorted by that percentage by which water supplies fell short of aggregate rights. Sacrifices were shared equally by all water users.

Brown *et. al.* (1982) have observed informal arrangements to share adversity among appropriators. Most administrative allocation arrangements, as in the California water districts, impose universal cutbacks, although not always in uniform proportions. Furthermore, Arizona requires increasingly stringent across-the-board reductions in ground water pumping by irrigators and industrial users to meet an eventual goal of attaining safe yield in three active management areas.

3. Water marketing, under which available water supplies were delivered to water users solely according to the marginal value of water in each use. This was interpreted to mean that generally higher-valued municipal demands would be satisfied first, followed by lower-valued agricultural demands. This option did not contradict the doctrine of prior appropriation but coupled it with the assumption that holders of senior water rights whose uses were low-valued (agriculture) could and would sell water to those whose uses were higher-valued (municipalities).

Both Arizona and California rely upon ground water and upon administrative allocation of water supplies much more heavily than do the other basin states. In Arizona in particular, groundwater accounts for over half of annual depletions, and even much of the surface water is allocated administratively by the Salt River Project. Pending disposition of Indian and other federal water rights issues in that state, the appropriation doctrine plays only a minor role in distributing the year-to-year burdens of water scarcity. This, coupled with the great current interest in how Arizona will use and pay for its Central Arizona Project (CAP) entitlement, led to the development of AZSIM (Booker, James F., 1993, unpublished manuscript), a model of Arizona's water economy for use in the SSD analyses, and to the formulation of unique intrastate water allocation options for Arizona to be used in AZCOL. Briefly, those three options are as follows:

1. Strict enforcement of the 1980 Arizona Groundwater Management Act (AGMA) with no subsidy to CAP agriculture. This legislation forbids further depletion (after 2025) of the aquifers underlying the Phoenix and Tucson Active Management Areas (AMAs). Under this option, those two areas rely increasingly upon CAP water, but little CAP water is used by irrigators due to its high cost relative to ground water. CAP use falls below its current levels and rises only slowly thereafter. This option potentially allows Arizona to lease or sell such water to other states.

2. Strict enforcement of AGMA and a similar restriction against ground water overdraft throughout the entire state, coupled with a subsidy to irrigators with CAP allocations. That subsidy is just sufficient to eliminate the cost difference between using such water and pumping ground water (such a subsidy is currently used in Arizona in the form of tiered CAP water rates for irrigators). Under this option, CAP water use is maximized within the state and the historic overdraft of ground water is ended.

3. Reliance upon recharge and underground storage of CAP water. This option resembles the first strict AGMA option but also includes large-scale recharge of CAP water to the state's aquifers. This water is thus made available, at cost, in years when CAP deliveries may be restricted. The result is that CAP deliveries are increased, compared to option one, and water is stored to meet future exigencies.

Interstate Operating Rule Options

The menu of optional interstate operating rules from which the participants could choose was more detailed, realistic, complex, and open-ended than was that for intrastate rules, as just described. It was the evaluation of these interstate rules which was a main purpose of the SSD research, so they will be described in greater detail than were the intrastate options. These options were identified by the SSD legal and institutional teams as points of institutional flexibility that would likely be tested during the course of a severe sustained drought (see MacDonnell *et. al.*, 1995). Each option was then tested for feasibility by the computer simulation team.

These operating rules were not complete and mutually exclusive options, as were those for intrastate decision making. Instead, they were more in the nature of component elements, which could be assembled in various ways to form complete sets of operating rules:

1. Uncompensated shorting of the Mexican treaty delivery obligation, in which the Secretary of Interior (SOI) decides how much Colorado River water to deliver to Mexico. Resulting savings are divided among states in the sub-basin (upper or lower) where the shortage exists.

2. Compensated shorting of the Mexican treaty delivery obligation, in which water allocation follows the previous rule, but the SOI then decides the amount of the compensation paid to Mexico and the distribution of that cost among the federal government and each of the basin states.

3. Revision of the operating criteria for Hoover Dam which alters the definition of a lower basin shortage and changes the amount by which CAP deliveries will be reduced when this shortage

condition is reached. Currently, a lower basin shortage is declared when the contents of Lake Mead drop below 13,359,000 acre-feet, at which time CAP diversions cannot exceed 800,000 acre-feet annually. Until recently, however, a lower basin shortage was not declared (prospectively, of course, since a lower basin shortage has not yet occurred) until Lake Mead fell below 10,762,000 acre-feet, but at that point CAP deliveries were reduced to no more than 450,000 acre-feet annually. Possible choices for the lower basin shortage declaration level and CAP diversion ceiling are not restricted to those listed above, but these rules should be adjusted in tandem. In other words, subjects could phase in CAP reductions gradually, as in the current rule set, or more abruptly, as in the earlier set. The current rules limit the size of initial cutbacks in Arizona's CAP diversions but raise the probability of such cutbacks, while the earlier rules were designed to maintain the minimum power pool in Lake Mead for as long as possible.

4. Revision of the operating criteria for Glen Canyon Dam, which carry out the required releases to the lower basin under the terms of the 1922 compact and which also strive to maintain hydropower production at Glen Canyon. Currently the Department of the Interior prospectively follows what is called the equalization rule. This rule now requires that 8,230,000 acre-feet (the objective minimum release) be released from Glen Canyon Dam each year, except under three contingencies. The first of those contingencies occurs when Lake Powell is full and inflow exceeds the lower basin delivery obligation of 8,230,000 acre-feet. At that time, water is spilled in sufficient quantities to prevent failure of Glen Canyon Dam. This rule need not concern us here because this contingency would not occur under drought conditions. The second contingency occurs when the contents of Lake Mead fall below those of Lake Powell, at which time releases in excess of 8,230,000 acre-feet are mandated to forestall a possibly needless failure to meet lower basin demands. Because this "equalization rule" is asymmetrical and may even be in violation of the terms of the 1922 compact, an initial option was to abandon it. The third contingency occurs when the sum of the contents of Lake Powell and expected annual inflow is less than 8,230,000 acre-feet, under which conditions the release is limited to the water actually available.

The participants suggested, and eventually adopted, a so-called reverse equalization rule, another option which would maintain the contents of Lake Powell equal to those of Lake Mead by reducing releases from Glen Canyon Dam below the 8,230,000 acre-foot standard whenever Powell was lower than Mead. This, in turn, generated a fourth option, which combined the equalization and reverse equalization rules. Under this rule, Powell and Mead would be fully equalized, essentially treating them as a single reservoir.

The Colorado River Compact requires that at least 75 million acre-feet be delivered at Lees Ferry in every ten-year period for use by the lower basin states. This is known as the ten-year moving average requirement. It stands in contrast to the fixed annual delivery obligation, called the objective minimum release, which is currently incorporated in the operating rules for Glen Canyon Dam. Our AZCOL model, unlike the Colorado River Model of Harding *et al.*, included the fixed annual delivery obligation rather than the ten-year moving average requirement of the compact. It is virtually certain that the ten-year moving average delivery obligation would be invoked in the event of a severe sustained drought. The adoption by the participants of the reverse equalization rule temporarily suspended adherence to the delivery obligation of the 1922 compact, whether implemented in the objective minimum release rule or the ten-year moving average rule.

5. Modification of the operating rules for upper basin reservoirs, which now attempt to maximize hydropower generation at Glen Canyon Dam. Water is released from these upper basin reservoirs as needed to maintain the minimum power pool in Lake Powell. The optional "store high" rule would maintain the contents of the upper basin reservoirs, subject to required deliveries in satisfaction of releases to the lower basin mandated by the 1922 compact.

6. Modification of the operating rules for all system reservoirs as necessary to meet the requirements of the Endangered Species Act (ESA). We are not aware that such modifications have yet been made. The basic difficulty is that, given adequate scientific knowledge at the time, these reservoirs could not have been built had the ESA been in effect when they were authorized (and had they not been excepted from its provisions). Changes in reservoir operating rules can delay some extinctions, but most of the damage is irreversible, save by removing the reservoirs (and even then, some species may already have been lost).

The optional rule provides that supplemental releases are made from reservoirs, whenever water exists in those reservoirs, in order to preserve endangered species in river reaches to comply with ESA. If activated, these supplemental releases are made to meet minimum stream flows required to maintain endangered species. These minimum stream flows are calculated as percentages of the long-term average flow for the stream reach according to criteria developed by Hardy (1994). In this case, five percent of long-term average flow is used to approximate these requirements.

7. Implementation of salinity control measures in addition to those already employed under United States Department of Agriculture (USDA) and Bureau of Reclamation programs. Options include: (a) reduction of agricultural source loading through on-farm efficiency measures such as lining of irrigation canals, irrigation scheduling, use of more efficient irrigation methods, or land leveling; (b) reduction of agricultural source loading by retirement of agricultural lands currently in production (reduction in agricultural demand); and (c) reduction of natural point and diffuse source loading through interception of saline waters and their disposal or reuse after treatment. USDA and Bureau of Reclamation estimates of costs and potential salt loading reduction are relied upon for implementation of these measures in AZCOL.

8. Utilization of the Yuma Desalting Complex to reduce salinity of Colorado River water reaching Mexico in order to comply with the U.S. obligation to Mexico under Minute 242 of the International Boundary and Water Commission agreement to deliver approximately 1.36 maf of water to Mexico upstream of Morelos Dam with an average annual salinity of no more than 115 parts per million (ppm) +/- 30 ppm over the average annual salinity of Colorado River waters at Imperial Dam in the U.S. Implementation of this option in AZCOL assumes that this facility is complete and that the capacity of the plant is 72 million gallons per day. Stand-by and variable costs of operation are included.

In addition, two interstate options were allowed only in the third game.

9. Interstate water marketing between the upper and lower basins has been discussed extensively in recent years but has not yet occurred. Some believe that there are legal barriers which must be erased for such marketing to occur. Others believe that the barriers are not legal but political. Therefore, water marketing was made an available option only in the third gaming exercise, when collective choice rules were changed from unanimous to bilateral approval. Then, any state could offer to lease some of its (unused) Colorado River water to other states for a stated price. The lease could be for a stated number of years or long-term (greater than the 38-year period considered by the study). A sale occurred only if another state agreed to the terms of the offer and if the Secretary of the Interior (SOI) approved.

10. Interstate water banking is another operating rule change which has been discussed in recent years. It, too, has not yet occurred and may be variously regarded as barred by current rules or potentially available, given sufficient political will. Again, this option was made available only in the third gaming exercise. Under its terms, any state could "deposit" some or all of its unused Colorado River water in a water bank account for that state, provided that a limit on the total amount of deposits by all states at one time was not exceeded. The water could be withdrawn automatically, whenever the banking state suffered a shortage, or it could be withdrawn on demand, according to instructions from the state. Deposits could not be transferred to another state's account. However, water could be banked by the purchasing state and later withdrawn or offered for sale (or offered before being withdrawn). Similarly, water could be purchased and then banked by the purchasing state. Limits borrowed from the California Water Banking Proposal were placed on the total amount of water a state was allowed to bank during the drought, in order to prevent large-scale negative impacts on non-consumptive values. Those limits are given in Table 2.

TABLE 2. Water Banking Limits on Amounts Transacted (thousands of acre-feet).

State	Quantity
Arizona	1400
California	2200
Colorado	1600
Nevada	200
New Mexico	300
Utah	700
Wyoming	400

RESULTS

As is shown in Table 3, proposals to change interstate management of the river that were made during the three games can be classified into five broad categories: salinity control, interbasin management of storage, endangered species protection, shorting of deliveries to Mexico, and permanent adjustment of California's basic allocation. Interbasin management of storage refers to proposals to equalize storage in the upper and lower basins by adopting a "reverse equalization" rule or a simple reduction in the required yearly delivery from the upper basin to the lower basin. Proposals in two of these categories – permanent adjustment of California's basic Colorado River allocation and shorting of deliveries to Mexico – were only made in one of the three games.

Salinity control was the focus of game one, in terms of the number of proposals, with six proposals eventually resulting in an agreement on how to apportion

TABLE 3. Nonbilateral Interstate Management Options Proposed.

Type of Proposal	Game 1 (Proposed\Adopted)	Game 2 (Proposed\Adopted)	Game 3 (Proposed\Adopted)
Salinity Control	6\1	0.5\0*	1\1
Interbasin Management of Storage	1\0	5.5\1*	1\1
Endangered Species Protection	3\1	1\1	1\1
Shorting of Mexican Deliveries	2\1		
Permanent Adjustment of California's Basic Allocation		1\0	
Total	**12\2**	**7\2**	**3\3**

*A reduction in the delivery requirement to the lower basin was proposed in return for upper basin salinity control. This proposal was, therefore, counted as half salinity control, half interbasin management of storage.

costs of a program to cut agricultural salt loading in the upper basin by 10 percent. Endangered species protection was also adopted in this game. In addition, the need for a "reverse equalization" rule was discovered in this game as the contents of Lake Mead stayed unexpectedly high and Lake Powell was drained at a relatively much faster rate. Current operating criteria for Glen Canyon Dam allow forward equalization to equalize the September 30 contents of Lakes Mead and Powell if the contents of Powell are greater than those of Mead. It was discovered that in order to avoid delay onset of upper basin shortages, a reverse equalization rule was needed. This rule was added to the model for games two and three but was not available in game one. A temporary reduction in the yearly delivery requirement from the upper basin to the lower basin was also proposed but required modifications of the model which were possible to complete only in time for games two and three, not game one.

Interbasin management of storage was the focus of the second game, partially as a result of the learning that had occurred in the first game. A reverse equalization rule was adopted after arriving at an agreement to compensate the lower basin if this rule change resulted in the draining of the contents of Mead below the Mead shortage declaration level at a time when the upper basin is unable to make full deliveries to the lower basin. The form of compensation was left unspecified, but if compensation were to be required and no compensation agreement could be reached, the upper basin states would be required to reduce consumption below their present perfected rights (which are, collectively, two million acre-feet). Compensation was not required, however, for the contents of Mead reached the shortage declaration level in years during which the upper basin made full deliveries to the lower basin.

The focus of game three was interstate water banking and water marketing. Bilateral negotiations between pairs of states were frequent and resulted in seven interstate water transfers and a like number of water banking arrangements, the latter usually but not always associated with water transfers. Every state except Nevada sold Colorado River water to California. Water sold to California totaled 5.8 million acre-feet over the 38 year simulation. Wyoming, Utah, and New Mexico sold water stored in their water bank accounts. Only Colorado used its water banking allotment to defray its shortages. The SOI promulgated additional interstate decisions without protest from the states. These actions included implementation of the reverse equalization rule, protection of endangered species, and utilization of the desalting plant at Yuma, Arizona, to meet international treaty requirements.

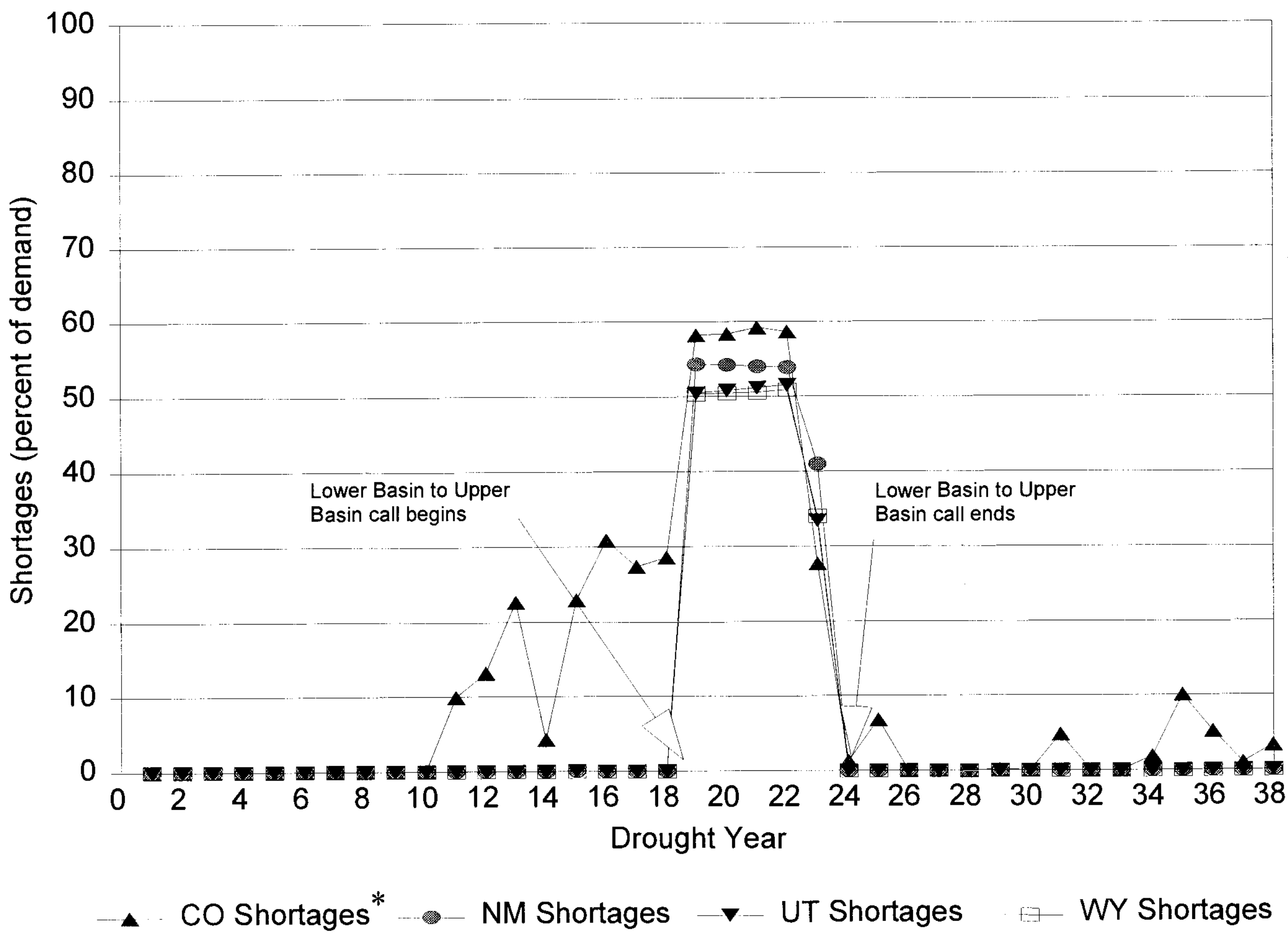
There are additional changes which are within the purview of the basin states themselves which were made during these games. The most obvious of these are the water allocation and management rules which the individual states administer within their own borders. Two state players made such changes, which may or may not have required legislative or court action to accomplish (governors in the West have substantial powers to temporarily alter water allocation rules during drought emergencies).

Summary of Drought Impacts by Category of Water Use

Consumptive Use Shortages. The majority of the drought-caused shortages each game occurred in the upper basin. Figure 1 shows yearly shortages as a percentage of requests for withdrawals in the upper basin by drought year for game one – the game in which upper basin shortages were the greatest. In each game, a lower to upper basin call triggered a reduction of consumption in the upper basin from maximum desire for water use to rights. Average yearly shortages suffered by upper basin states in game one ranged from 52 percent for Colorado to 47 percent for Wyoming. Average shortages were less severe and occurred in fewer years in the second and third games. Average shortages during compact call years ranged from 43 percent for Colorado to 32 percent for Wyoming in game two and from 54 percent in Utah to 46 percent in Wyoming for game three. There were call-induced upper basin shortages for five years in game one, three years in game two, and four years in game three. Reverse equalization rules adopted in games two and three were responsible for reducing the number of years in which a compact call and shortages existed.

The results of each game erroneously showed that shortages in Colorado occurred sooner and lasted longer than in other upper basin states. Colorado shortages which did not occur during the compact call were a result of excessive aggregation of Colorado demands in the model and do not reflect any real supply limitations. The number of withdrawal points in Colorado has since been expanded from three to five, and sufficient geographic realism has been achieved. However, not enough time was available during the games in order to make these changes. Therefore, during the games, the Colorado player was advised that true Colorado shortages would occur only in years during which a compact call is in effect. The severity of Colorado shortages during years in which a compact call exists is correctly reported by the model.

Shortages in the lower basin occurred in all three games. However, in each case, only the first stage of lower basin shortages was reached – that of reducing the maximum CAP delivery allowed. The degree to which these shortages affected Arizona water users



* Colorado shortages in years in which a compact call does not exist are a result of excessive aggregation of demands in the model and are to be ignored. Severity of Colorado shortages is correctly represented for years in which a compact call is in effect.

Figure 1. Upper Basin Shortages, Percent of Demand, Game 1.

depended upon the overall intrastate management policy adopted by the Arizona player during the shortages in each game. In game one, Arizona increased its desire for CAP water prior to the onset of lower basin shortages by approving a subsidy of agricultural use of CAP water combined with enforcement of safe-yield ground water use restrictions to all Arizona Active Management Areas. As a result, Arizona suffered average shortages of 0.7 million acre-feet per year over 16 years, compared to its normal maximum CAP allotment, and an average of 0.895 million acre-feet over 21 years compared to the maximum desire for water use under this policy. Arizona adopted different policies in the two other games. In game two, Arizona did not support a subsidy to CAP agriculture and suffered no shortages when its maximum allowable CAP delivery was cut. In game three, also with no subsidy to CAP agriculture, Arizona suffered minor CAP agricultural shortages, averaging 45 thousand acre-feet for four years of the game, only two of which were consecutive. Arizona water users did not suffer any cutbacks in water use in game three, however, for Arizona drew upon recharged CAP water to make up for cutbacks in CAP deliveries.

The other lower basin states besides Arizona did not suffer a drought-caused shortage at any time during the three games. California can be said to be in a chronic state of shortage with a basic allocation of 4.4 million acre feet and a maximum desire for water use around 5.2 million acre-feet. These chronic shortages are independent of the impacts of basin-wide drought and will only be discussed in terms of California's desire for more Colorado River water.

Hydropower. Sales from power generated by basin reservoirs remained relatively comparable over the three games. Average yearly benefits from hydropower were almost identical in all games, averaging about $382 million in each game, or about 70 percent of the highest valued year of hydropower benefits in the simulation. Game three hydropower benefits would have been lower than in the other games had California used more of its banked water, thus draining the contents of Mead below minimum power pool sooner or for a longer duration.

Recreation. Monetary benefits from recreation was also very similar across games, ranging from a yearly average of $349 million in game one to $342 million in game three, or from 79 percent to 85 percent of the highest valued year of recreation benefits in the respective simulations. Higher benefits from recreation at Lake Mead in game one due to higher lake levels early in the drought sequence accounted for most of the difference across games.

Salinity Control. Salinity damages in each game were greatly affected by the salinity management policies adopted. No salinity control measures were agreed upon in game two, resulting in salinity damages of $52 million in the upper basin and $188 million in the lower basin. There were also 12 years of the 38-year drought sequence in which Minute 242 was violated. By contrast, in game one, a 10 percent reduction in agricultural salt loading was agreed upon by the players. Compared to game two, the program saved about $1.47 billion in average yearly salinity damages or $273 million after subtracting the project cost. In addition, there were four less violations of Minute 242 in game one as compared to game two.

In game three, the desalting plant at Yuma was activated to help meet the obligation to Mexico outlined in Minute 242. The plant was effective in reducing violations of Minute 242, with six less violations than in game two and two less violations than in game one. In addition, the desalting plant reduced the severity of the six violations in game three. However, at an average cost of $394 per acre-foot of less salty water delivered from the Yuma plant, it is necessary to note that other options such as on-farm reduction of salt loading could be more cost effective in reaching the same result.

Environmental Attributes. Environmental specialists on the SSD research team identified seven types of environmental impacts and 16 critical locations for assessment purposes (Hardy, 1994). Impacts were estimated on a four-part ordinal scale. The most severe impact level, in the case of threatened and endangered species, represents extirpation of the species at that location.

Most instances of environmental deterioration are to some degree reversible, but in the case of threatened and endangered species, losses are not so easily reversible. Complete extinction of a species is clearly irreversible, but localized extirpations are probably reversible, given enough time and effort and provided that breeding stocks exist elsewhere in the system.

With an instance of extirpation defined as complete elimination of a single species at a single location in a single year, there were 21 instances of extirpation of threatened or endangered species in game one, 32 in game two, and 30 in game three. These extirpations occurred in Flaming Gorge, Navajo, and Lake Powell reservoirs, and in the Green River below Flaming Gorge. All of the reservoir extirpations were eventually reversed, but that in the Green River was not.

The player representing the Secretary of the Interior invoked the Endangered Species Act to modify reservoir release rules and protect these species in each game. The player in the first game acted to do so just five years into the drought period. The (different) player who assumed this role in the second and third games waited until the 18th year to do so, which explains the superior record in protecting those species in the first game.

No corresponding special changes in operating rules were made to mitigate environmental impacts other than those upon threatened and endangered species impacts such as wetlands, national wildlife refuges, and native non-listed fish. Consequently, these impacts were negative in 75 percent of the instances. This is so not only because there may be no clear legal basis for mitigating these other impacts but also because there was less understanding on the part of the players (none of whom was an environmental scientist) as to what rule changes might have been effective in doing so.

EVALUATION AND DISCUSSION

We analyze the results of the three gaming exercises from the perspective of the two purposes for which the exercises were conducted. The first of these purposes was to identify for further study those *operating* options which showed the most promise for mitigating drought impacts and which could be adopted and implemented without Congressional action (new legislation) or additional Supreme Court decisions. We also compare the results of the three gaming exercises, in evaluating alternative *collective choice* institutions. Three such options were investigated, as described previously. These options, unlike those at the operating level, were determined before the gaming occurred and were not within the ability of the players to change. Nonetheless, it is the outcomes of the operating rules which the players selected in each game which permit us to compare and evaluate these collective choice options.

Multiple Decision Criteria Exist

In the SSD gaming exercises, we attempted to display to the players the potential impacts associated with all of the plausible management objectives (water supply, hydroelectric power generation, water-based recreation, water quality control, and environmental preservation) so that each player could give whatever weight he chose to each of them. Although there were differences from state to state and from game to game, each state player was shown about 100 items of information (some of which, like reservoir contents and releases, were not impact measures) for each year, for a period of no more than five years, at each decision point. The cognitive task for each player was impossibly difficult for decision making within the half hour *de facto* limit which applied. It would be easier for state water managers operating in real time. Still, psychological research has firmly established that the consistency and discrimination of human judgments degrades rapidly as the number of criteria increases.

In the gaming exercises, we chose to present impacts in each category in physical terms and also to display the aggregate monetary impact, as used in the policy capture research. We thus left up to each individual player whether to use the monetary variable or to attempt to trade off a large number of physical impact measures. This was done in part because the monetary variable was so highly aggregated that it obscured possibly relevant distributional considerations and partly because the research team was well aware that water decision makers are traditionally disinclined to maximize net monetary benefits.

The cognitive task of balancing or trading off the five broad management objectives of quantitative water deliveries, hydroelectric power generation, reservoir recreation, water quality control, and environmental preservation is well within the capabilities of human judgment, provided that all of the many detailed impact categories could be satisfactorily aggregated to this level of generality and abstraction and provided that the weights and functional forms of the relevant judgment policy were well known. However, such information is never available, since we are referring to a political process of determining and expressing societal policy objectives, not those of individuals.

Decision Criteria are Highly Competitive

There are many other competitive relationships between water management purposes in the Colorado River Basin. Conflicts between hydropower and recreational and environmental purposes have been prominent recently. Reservoir recreation and whitewater recreation frequently conflict. Reservoir releases for salinity control may conflict with those for power generation. Most obvious of all is the basic conflict between consumptive (water supply) water uses and all of these non-consumptive water uses. And these conflicts between objectives are in addition to the conflicts between states which have characterized the basin for all of this century.

The Law of the River seems to offer clear guidelines to resolving conflicts between competitive purposes and states. To paraphrase, those guidelines state that consumptive water uses must be favored above nonconsumptive ones, that the lower basin holds rights senior to those of the upper basin, that California rights are senior to Arizona's rights to Central Arizona Project (CAP) water, and that upper basin states share drought risks, in the event of a need for curtailment of use, in proportion to the previous year's distribution of water use between upper basin states. But other rules established since 1922 cloud that conclusion. The Endangered Species Act may supersede the Law of the River if the two conflict, and there has been much speculation and investigation of this possibility in recent years. The Clean Water Act may offer similar possibilities for conflict, although it has received less attention thus far. And the issue of federal reserved rights casts a major cloud over the inviolability of the criteria implicit in the Law of the River. But the seemingly greatest source of conflict, insofar as the results of the SSD gaming has shown, lies in the competitive nature of the technical relationship between consumptive water uses on the one hand and non-consumptive ones on the other. Existing rules, at least those which are formally codified, give little standing to the nonconsumptive purposes of river management. Certainly the players in the SSD drought gaming exercises gave hydropower and recreation short shrift. Lack of attention to hydropower benefits was probably encouraged, however, by our inability to identify state-specific hydropower benefits.

The first and, apparently, foremost decision criterion used by players in the gaming exercises to evaluate operating rules for the Colorado River interstate water management system (hereafter, CRIWMS) was quantitative water deliveries. Historically, each of the basin states has attempted to establish and safeguard its share of the limited quantity of water yielded by the hydrologic system. It is not surprising that the players in the gaming exercise, who were attempting to play the roles of state water decision makers, should focus heavily upon this decision criterion.

The Playing Field Is Not Level

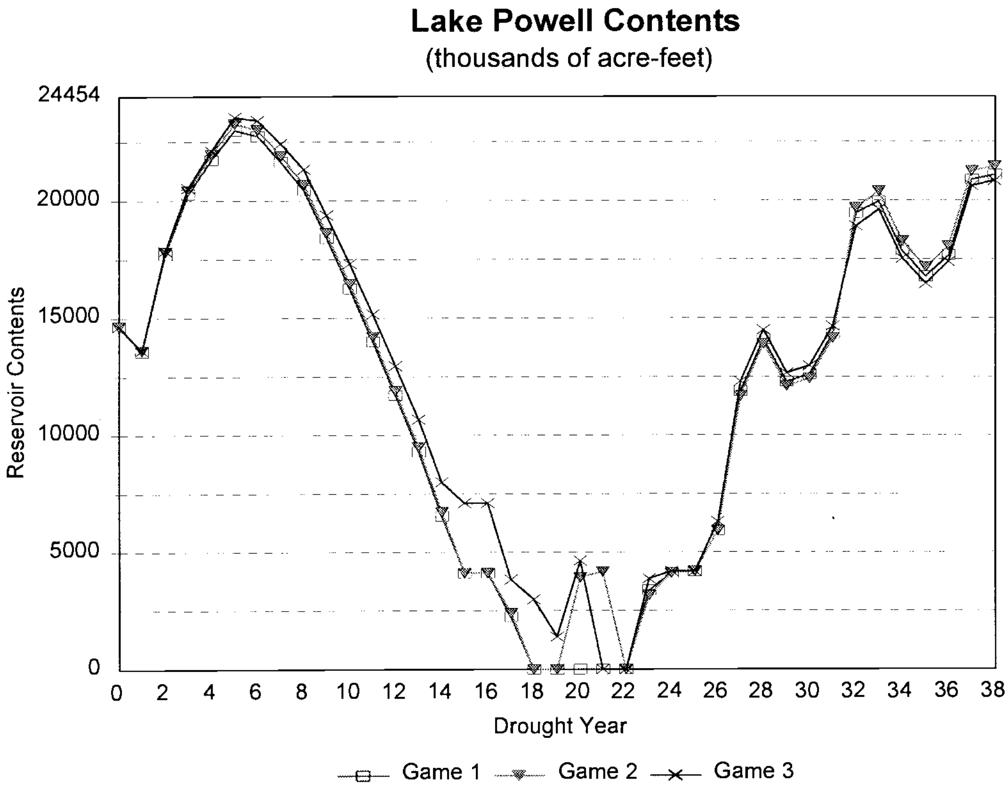
Consumptive Water Uses Are Well-Protected From Drought. Figure 2 shows a trace of reservoir contents over each drought game for the two major Colorado River basin reservoirs – Lake Powell and Lake Mead. One role of the substantial storage capacity represented by Lakes Mead and Powell, and by the other system reservoirs, of course, is to mitigate drought impacts by storing water in wet years and delivering it in dry years. Since that storage capacity is large, amounting to about four times the mean annual flow of the river, water uses in the Colorado Basin are well protected against short droughts. However, the severe sustained drought produced shortages throughout both subbasins and drained Lake Powell to dead storage in all games. Despite these shortages, the system of federal reservoirs, together with the rules under which it is now operated, provide exceptional drought protection to consumptive uses in the lower basin states and good drought protection to such uses in all of the upper basin states.

By far the largest shortages are those suffered by California. But these shortages, which represent California's "surplus" demands (deliveries which are in excess of California's basic entitlement of 4.4 million acre-feet and which are made only in years when sufficient water is available in the lower basin), could hardly be said to be drought-caused, since they occur in each and every year. Upper basin shortages are concentrated in a few years but cause substantial reductions in water deliveries at the depth of the drought.

In year 19, the most severe year of the drought, basin-wide shortages amounted to 12.6 percent of basin-wide water demand, and upper basin shortages amounted to from 50 to 60 percent of upper basin demand. These shortages are considerably lower than some of the shortages which were imposed upon California water users in the last year of the recent (1987-1992) drought in that state. The uneven distribution of drought shortages throughout the basin suggests that institutional changes which distribute those impacts more evenly could reduce hardship at modest cost.

In sum, when seen from the perspective of consumptive water uses, drought-caused shortages were not so large for the basin as a whole as to motivate the players to take heroic measures to mitigate them. Indeed, as will be seen, the results of the three games, played under rather different sets of decision-making rules at the collective choice level, were more remarkable for their similarity than for their differences. There are two plausible explanations for this similarity, the first arising from lack of a significant drought problem and the second from collective choice rules, under all three options, which made changes in operating rules difficult to achieve.

Nonconsumptive Water Uses Are Highly Vulnerable to Drought. Nonconsumptive uses are far more vulnerable to drought than are consumptive water uses, at least when the system is managed pursuant to current rules. Figure 3 shows monetary benefits from nonconsumptive and consumptive uses from Game two. Results from Games one and three are virtually identical. Among the nonconsumptive uses, water-based recreation is not as vulnerable to drought as is hydropower generation, which falls to



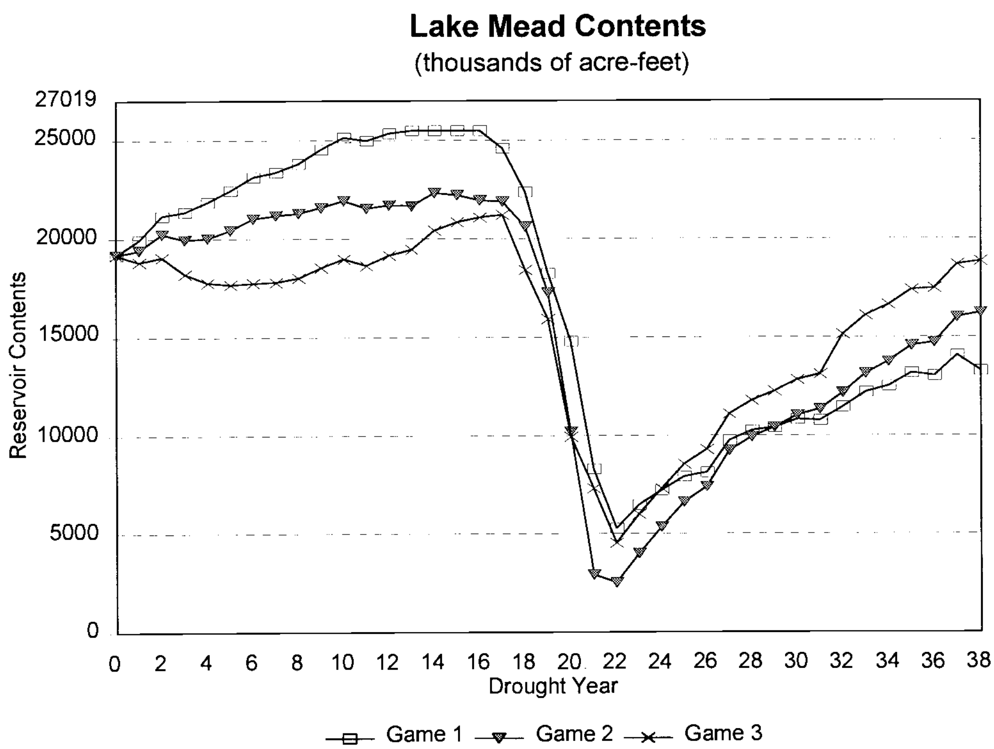


Figure 2. Lake Powell and Lake Mead End-of-Year Contents.

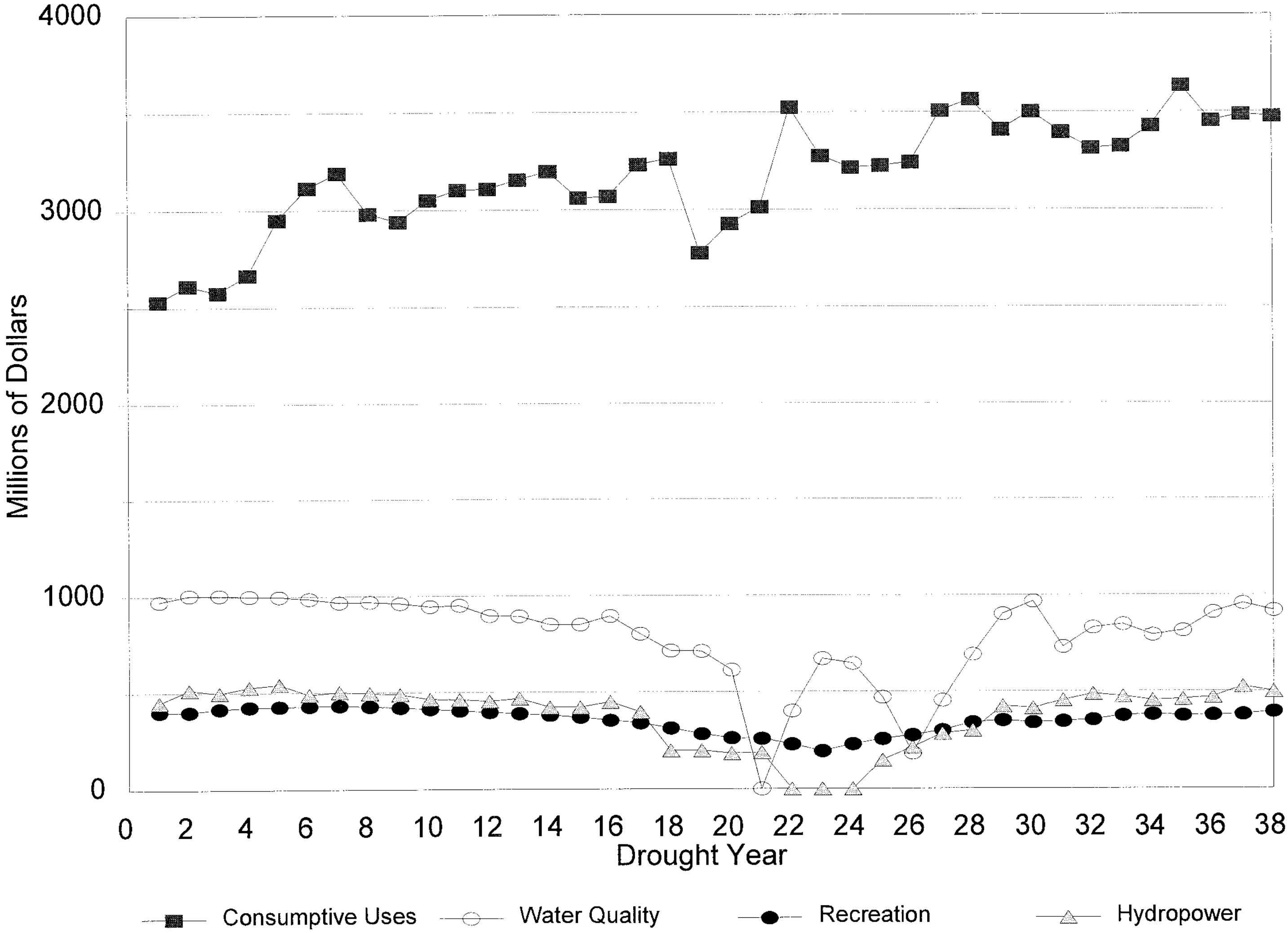


Figure 3. Benefits from Consumptive and Nonconsumptive Uses, Game 2.

zero at the depth of the drought (power is no longer generated when reservoir levels drop below the minimum power pool, even though releases of water can continue to be made). Hydropower was valued conservatively, following Booker *et. al.* (1994). Recreation benefits fall to about half of their normal level at the depth of the drought. Salinity damages rise to at least equal recreational losses.

None of this is to say that drought-caused losses could be avoided through adopting different water management institutions, as was largely possible in the case of consumptive water uses. Because there is less inflow in drought years, there must be less hydropower generation, even if all withdrawals for consumptive uses were to cease. However, by sustaining withdrawals for consumptive uses above levels which would have characterized an unmanaged drought, the Colorado River management system has increased the severity of drought-related hydropower losses.

A severe sustained drought is likely to cause adverse impacts upon a number of environmental attributes on the Colorado River. Environmental values are not mentioned in the priorities set out in the Law of the River and have not been recognized as a beneficial use in most western states' water codes until recently. Some states have enacted instream flow protection programs, but instream flow rights are usually the junior rights on often heavily appropriated rivers. In addition, the lack of developed markets for environmental attributes means that they are often not included in valuations and decisions made according to a monetary scale. And, because of the public goods nature of environmental values, even if a monetary measure was developed for environmental attributes, it is likely that the monetary value assigned would underestimate the true societal utility of those attributes.

One way around the problem of the non-market nature of environmental attributes is to develop environmental quality standards according to biological criteria and to identify actions that are appropriate to prevent those values from falling below the criteria. This approach was used in this study, but only for threatened or endangered species protection. The task of identifying what actions would be appropriate to protect all of environmental attributes identified by SSD environmental scientists, which includes wetlands and riparian areas, native nonlisted fish, and national wildlife refuges, is difficult outside of the scope of this study. In each game, players adopted the option that was well identified to protect endangered species – that of maintaining minimum flows in stream reaches with endangered species by using releases from storage reservoirs, if water to do so exists in those reservoirs. In spite of this action, even though the ESA option was implemented early in the first game, there were still at least 21 instances of extirpation of threatened or endangered species in each game.

Drought Risk is Greatest in the Upper Basin. The 1922 Colorado River Compact essentially gives the lower basin states seniority in claiming the first 7.5 million acre-feet of Colorado River flows, although it is often held that half of the delivery obligation to Mexico must come out of that allotment. Only after the full lower basin obligation has been met can the upper basin states begin to satisfy their post-1922 demands. Thus, the lower basin has a legal right to at least the first 6.75 million acre-feet of water flowing in the Colorado, after the present perfected rights of approximately two million acre-feet have been satisfied.

On average, the upper basin share may be expected to amount to about 5.5 million acre-feet, including present perfected rights, since the mean annual undepleted flow of the river is now thought to be well below the 16.4 million acre-feet upon which the 1922 compact negotiations were based. Current upper basin withdrawals amount to over four million acre-feet, so the system is nearing the point where demand is equal to supply, even in normal years. Shortages begin to occur at that point, and they are borne disproportionately by the upper basin states.

Again, California could be said to be in a state of chronic water shortage, but it and the other lower basin states are virtually drought-proof. By the 1922 compact agreement, the lower basin gained the assurance of a stable water supply at the expense of limiting its long-term mean withdrawals to less than the amount needed to meet its demands. Conversely, the upper basin states gained a long-term limitation on the lower basin's share of the system yield, at the cost of assuming almost the entire drought risk of the entire basin. From a drought protection standpoint and considering only consumptive water uses, the lower basin states enjoy a remarkably superior position to that of the upper basin. By the same token, the price paid for that advantage has been high, both in terms of foregoing greater long-term access to normal flows and in terms of impacts upon nonconsumptive water uses (these impacts bear most heavily upon the populous lower basin).

Only Minor Changes Can be Made Under Existing Rules

The most striking aspect of the outcomes of the three SSD drought gaming exercises is their similarity. Upper basin shortages were similar in the first and third games, although they were about one-fourth lower in the second game. They were lower in the second game because the players were able to agree on and implement a reverse equalization rule, which resulted in two fewer years of upper basin shortages. But upper basin shortages rose again (although not greatly) in the third game, despite the adoption of the reverse equalization rule, because some upper basin states sold banked water to California which could have been used to defray shortages.

The decline in lower basin shortages between the first and second games is due to unilateral actions taken by the Arizona player in changing that state's internal water management rules. It does not reflect actions taken at the collective choice level. California's chronic shortages were reduced in the third game as a consequence of that state's purchases of upper basin and Arizona water.

Water banking and water marketing provisions in the third game were heavily used by basin states. However, only Colorado used water banking to stem drought-induced losses. Colorado reduced its game three shortages during the first year of the compact call to 36 percent of maximum desire for water use from 58 percent in the same year of previous games. Had upper basin states other than Colorado also used their banking allotments to defray drought-caused shortages, overall upper basin shortages in game three would still have been substantial but closer to the level of game two.

The observed differences in shortages in the two subbasins between the three games are interesting and not insignificant, but they are very minor changes when seen from the perspective of drought outcomes in general. The players simply were unable to substantially change those outcomes through negotiating changes in the operating rules. They did, however, employ a very narrow set of decision criteria throughout all of the games. We believe that the players attempted almost single-mindedly to maximize Colorado River water deliveries to their respective states, within and up to the limits of their compact entitlements. The existing operating rules are hard to improve upon, at least for this severe of a drought, from the limited perspective of coming as close as is possible to fulfilling compact entitlements.

Adoption of salinity control measures and endangered species protection were the other operational rule changes that states made an effort to consider in each game. And while adoption of a salinity control program was cost effective in stemming salinity damages in game one and endangered species protection measures were adapted in each game, only reductions in consumptive uses could have significantly reduced damages to these non-consumptive uses.

Intrastate Drought Management is Most Effective

Two state players, those representing Arizona and Wyoming, were more successful in managing drought, at least by some criteria, than were most others. The Arizona player was able to reduce Arizona's demand for consumptive uses of Colorado River (CAP) water progressively, from 2.5 to under 2 million acre-feet annually over the three games, while at the same time virtually eliminating drought-caused water shortages. In doing so, drought-related monetary losses to Arizona were reduced by $23 million, on an average annual basis (the reduction was much greater for the worst drought years). The Arizona player's success was due to astute *interstate* water marketing transactions in the third game, coupled with the choice of *intrastate* water management rules which were consistent with interstate water banking and marketing behavior.

The Arizona player began the first game with strict enforcement of the Arizona Groundwater Management Act, which meant that Phoenix and Tucson AMAs were required to meet the safe yield groundwater management goal and thus purchase CAP water to avoid overpumping. Other areas of the state were not so restricted, electing to pump ground water in preference to purchasing the more expensive CAP water. As the drought worsened, however, this player shifted to a state policy which subsidized CAP water use and imposed the safe yield goal on all of the state. As a result, Arizona increased its use of CAP water to its compact entitlement (which reduced deliveries somewhat at the depth of the drought) but incurred financial penalties through subsidizing agricultural uses of CAP water.

The Arizona player, perhaps as a result of learning from the results of the first game, began the second game with yet a different state water management policy than either of those which he had used in the first game. This third policy eliminated the costly agricultural subsidy of the second option and resembled the first policy, except that it employed artificial recharge of all otherwise unused CAP water, also a costly measure. The recharged water was then available during the drought so that Arizona was at least prospectively able to mitigate its drought shortages and adapt to reduced CAP deliveries. In fact, the Arizona player reverted to the first (safe yield) policy half way through the drought period, perhaps in anticipation of relying upon the recharged water at that point, but that stored water was never used because water users could not afford it.

The Arizona player began the third game using the same third (CAP recharge) policy option which he had tried in the second game. However, he quickly reverted to the original (safe yield) policy with which he began the first game, and he remained with that policy for the last 31 years of the drought period. Instead, Arizona became a seller of CAP water to other states which were experiencing drought shortages and was able to profit handsomely without suffering shortages itself.

The Wyoming player in the first game was able to achieve significantly higher water-related net benefits than the (different) player in the third game, despite the fact that Wyoming demand (for consumptive uses), supply (diversions), and shortages were identical in both games. The Wyoming player in the first game also achieved a higher level of benefits than did the (different) player in the second game, even though the player in the second game was able, acting in concert with the other players at the collective choice level, to adopt a reverse equalization rule and thereby reduce upper basin shortages appreciably.

The Wyoming player in the first game selected a change in intrastate water allocation rules which enabled free marketing of water between agriculture and municipalities. The resultant drought-year leases increased benefits to both farmers and municipalities and constituted a more effective drought management strategy, from a monetary perspective at least, than Wyoming was able to achieve through actions taken at the collective choice level in the second game or by interstate water banking and marketing transactions in the third game.

Players who did not adjust their intrastate options seemed to take the general water management philosophies of their states as immutable even in the time of drought. An initial designation of the intrastate option for each state was made by the game controller in accordance with what was believed to represent the general water management philosophy of each state. The player for Utah in the first game disagreed with a designation for Utah of option one – strict prior appropriation – and made an initial switch to option three, allowing intrastate water marketing. This designation was not changed in the remainder of that game or the other two games. Even when reminded that changes in intrastate option were allowed, players besides those for Arizona and for Wyoming in the first game seemed uninterested in using intrastate management option changes to manage drought impacts.

SUMMARY

The SSD gaming exercises were conducted within the limited context of those changes in interstate water allocation (operating rules) believed to be attainable without changes in statutes or judicial interpretations. The gaming was conducted under collective choice rules which approximate those currently in effect and then was repeated twice, each time under a modified set of operating rules but, again, including only those changes which were thought to be attainable without legislative or legal action.

One of the principal findings of the gaming exercises was how little difference these changes in collective choice rules made. The operating rules selected by the players were very similar in the three games, and the resultant impacts upon water allocation, management, and use were correspondingly similar. The only really significant difference was that the players were able to modify the existing equalization rule in both the second and third games, thus somewhat easing upper basin shortages at little cost to the lower basin.

A second principal finding was that existing operating rules (and those chosen in the second and third games) favor consumptive water uses over such nonconsumptive uses as hydroelectric power generation, environmental protection, salinity control, and recreation. The extent of this favoritism (technically, the tradeoff ratio) is out of all proportion to what are, arguably, the public values involved. This conclusion emerges even when such nonmonetary values as environmental protection are discounted completely. It is even stronger if reasonable weight is given to these nonmarket factors.

A third principal finding is that existing decision-making institutions for interstate water allocation and management are designed to resolve conflicts between states acting exclusively in their own self-interests. They are not designed for discovering what the collective or common interest may be, unless that common interest is taken to comprise only resolution of such interest conflicts. Still less are they designed to facilitate action in the common interest, should it be revealed.

The fourth principal finding is that the existing operating rules needlessly limit California's long-term water supplies while needlessly increasing the upper basin's vulnerability to short-term drought. It would be relatively inexpensive for the upper basin and Arizona to reduce their long term claims upon Colorado River water in order to enable California to meet demands which already exist. It would be similarly inexpensive for California because of the high priority position in the lower basin of its basic apportionment and the well insulated position of the lower basin relative to the upper basin in the event of a severe sustained drought, to agree to share the burden of accommodating future drought shortages more equally, thus relieving what could be traumatic shortages in upper basin states. This finding reveals a clear opportunity for grasping that most desirable of conflict resolution possibilities, the positive sum solution in which there are only winners and no losers.

APPENDIX I
SYSTEM CONDITION INDICATORS USED AS "TRIGGER POINTS" IN AZCOL

Surplus: Declaration of lower basin surplus.

- The contents of Lake Mead plus the projected inflow are greater than the capacity of Lake Mead minus the scheduled deliveries to the lower basin.

Normal: No lower basin surplus and no upper basin shortage.

- Mead contents less than capacity.
- Powell not empty.

Shortage 1: There are upper basin shortages but no lower basin shortage.

- Powell empty.
- Mead greater than lower basin shortage declaration level.

Shortage 2: The first stage of lower basin shortages.

- Mead is less than lower basin shortage declaration level. CAP deliveries are reduced to their "shortage" delivery level.

Shortage 3: Second stage of lower basin shortages.

- Mead plus inflow not large enough to support full level of CAP "shortage" deliveries. CAP deliveries are further reduced or entirely eliminated.

Shortage 4: Third stage of lower basin shortages.

- Mead plus inflow not large enough to satisfy lower basin rights senior to CAP plus Mexican obligation. Proportional reductions rights senior to CAP are instituted.

Shortage 1 represents a situation where a call is placed on the river by the lower basin to the upper basin in order to maintain full deliveries at Lees Ferry from the upper basin to the lower basin, while the contents of Mead remain above the Mead shortage declaration level. In the case of a call, the upper basin states would be required to restrict use of Colorado River water to their rights as determined by the Upper Colorado River Basin Compact. Shortage conditions 2 through 4 may exist without a lower basin to upper basin call. A compact call indicator was used in addition to the shortage stage indicators to allow for this possibility.

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MITIGATING IMPACTS OF A SEVERE SUSTAINED DROUGHT ON COLORADO RIVER WATER RESOURCES[1]

Taiye B. Sangoyomi and Benjamin L. Harding[2]

ABSTRACT: We evaluated the effects of institutional responses developed for coping with a severe sustained drought (SSD) in the Colorado River Basin on selected system variables using a SSD inflow hydrology derived from the drought which occurred in the Colorado River basin from 1579-1616. Institutional responses considered are reverse equalization, salinity reduction, minimum flow requirements, and temporary suspension of the delivery obligation of the Colorado River Compact. Selected system variables (reservoir contents, streamflows, consumptive uses, salinity, and power generation) from scenarios incorporating the drought-coping responses were compared to those from Baseline conditions using the current operating criteria. The coping responses successfully mitigated some impacts of the SSD on consumptive uses in the Upper Basin with only slight impacts on consumptive uses in the Lower Basin, and successfully maintained specified minimum streamflows throughout the drought with no apparent effect on consumptive uses. The impacts of the coping responses on other system variables were not as clear cut. We also assessed the effects of the drought-coping responses to normal and wet hydrologic conditions to determine if they were overly conservative. The results show that the rules would have inconsequential effects on the system during normal and wet years.
(KEY TERMS:water resources planning; water policy/regulation/decision making; drought; water management; water law; social and political; irrigation; water quality; simulation.)

INTRODUCTION

Several drought-coping responses for mitigating the impacts of a severe sustained drought (SSD) in the Colorado River Basin were developed during interactive games (Henderson and Lord, 1995). These responses include shorting Mexico deliveries, changing the operation of Lake Mead with respect to the shortage level, changing the operation of Lake Powell to include a reverse equalization rule, implementing minimum streamflows to preserve endangered species in river reaches, reducing salinity through various measures, water marketing to lessen the effects of the drought, water banking, and intrastate drought-management options.

In this paper, we assess, from a water resources perspective, the usefulness of three of the coping responses that had the most visible effect on mitigating the impact of the SSD across a wide range of hydrologic conditions, using a monthly simulation model of the Colorado River System, the Colorado River Model (CRM). The three measures are reverse equalization, minimum streamflow specifications, and salinity reduction.

The CRM was developed over a twelve-year period by Hydrosphere. It emulates the USBR Colorado River Simulation Model (CRSM) (Schuster, 1987; 1988a; 1988b). The model is based on a network flow archetype (Texas Water Development Board, 1972; Clasen, 1968; Barr *et. al.*, 1974) and represents 14 reservoirs, 29 inflow points, and 265 withdrawal points within the system. The CRM is configured to simulate the "Law of the River" – the various statutes, compacts, treaties, court decisions, regulations, agreements, and formal operating criteria that govern the use of water in the Colorado River and its tributaries. A previous version of the model was used by Brown *et al.* (1988, 1990) in a study of the disposition of streamflow increases from the Arapaho National Forest. A complete description of the Colorado River Model can be found in Hydrosphere (1994).

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PHYSICAL SYSTEM

The Colorado River basin drains approximately 243,000 square miles contained within the states of Colorado, Wyoming, Utah, New Mexico, Nevada, Arizona, California, and parts of the Mexican states of Baja, California, and Sonora (Figure 1). The basin is divided both geographically and politically at Lee Ferry, just downstream of the point where the river crosses the Arizona-Utah border. The Upper Basin includes lands in the states of Colorado, New Mexico, Utah, Wyoming, and a small part of Northern Arizona, and is the principal source of inflow into the Colorado River system. The Lower Basin includes lands in the states of Arizona, California, Nevada, and New Mexico.

Many reservoirs alter the natural flow of the Colorado River. The 14 reservoirs modeled in the CRM contain a total active capacity of 61,375,000 acre-foot. The two principal reservoirs, Lake Powell and Lake Mead (formed by Glen Canyon and Hoover Dams, respectively), provide over 50 million acre-feet (maf) of storage. Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin. The Lower Basin diversions tend to be larger and considerably fewer in number. A more complete description of the physical system can be found in Schuster (1987) and Hydrosphere (1994).

INSTITUTIONAL SETTING

The allocation of water within the Colorado River Basin is constrained within an institutional setting which has evolved from judicial, statutory, and administrative decisions collectively known as the Law of the River. These include the Colorado River Compact (CRC) (1922), the Boulder Canyon Project Act (1929), the California Seven Party Agreement (1931), the Mexican Water Treaty (1944), the Upper Colorado River Basin Compact (1948), the Colorado River Storage Project Act (1956), the Supreme Court Decree in Arizona v. California (1963), the U.S. Army Corps of Engineers Water Control Manual for Flood Control, water delivery contracts, and the Criteria for Coordinated Long-Range operation of Colorado River Reservoirs (Operating Criteria), among others. The CRC of 1922 apportioned the flow of the river between the Upper Basin States (Arizona, Colorado, New Mexico, Utah, and Wyoming) and the Lower Basin States (Arizona, California, and Nevada); the CRC also required that the Upper Basin deliver a 10-year moving average flow of 7.5 maf to the Lower Basin at Lee Ferry. Summaries of the other governing laws can be found in Meyers (1966) and Nathanson (1978).

INFLOW HYDROLOGY

Two inflow sets were used in this study. They represent natural flows at 29 inflow points in the Colorado River Basin. The first is the SSD inflow set used for evaluating the coping responses under a drought condition. The 38-year SSD inflow set was derived from the drought which occurred in the Colorado River basin from 1579-1616, which was found to be the most severe in the over 500 years of reconstructed streamflow period. The annual flows within the critical period (from 1579 to 1600) were rearranged in a descending order, resulting in a clustering of the low flows about a single point, and thereby producing the SSD configuration. It is the same as the inflow hydrology used in Harding *et al.* (1995) and is described in Tarboton (1995).

The second inflow set is a synthetic streamflow trace used for evaluating the coping responses under "normal" and "wet" hydrologic conditions. The synthetic trace was developed from the statistics of observed Colorado River flows for the period 1931 through 1983, which has a mean of 13.5 maf/yr at Lee Ferry. This mean value is approximately equal to the long-term mean of flows at Lee Ferry reconstructed from tree ring records from 1520 to 1961 (Stockton and Jacoby, 1976). The synthetic trace has a mean of 13.51 maf/yr, a median value of 13.09 maf, a minimum of 4.76 maf/yr, and a maximum of 34.92 maf/yr. It was developed using the statistical streamflow package SPIGOT (Grygier and Stedinger, 1990a; 1990b).

DEPLETIONS

The same set of depletions (diversions minus return flows) were used in all the simulations reported in this study. The depletion set cover a 38-year period at 265 locations within the basin. It is the same as that used in Harding *et al.* (1995) and is the "medium" level of projected future depletions described in Booker and Colby (1995). Total depletions increase over the 38-year period of the simulations, beginning with estimates of actual water use for 1992 and progressing to projected values for subsequent years. The depletion estimates were, for the most part, derived from data developed by the USBR for its 1991 Annual Operating Plan, dated July 22, 1991. The depletion level assumes demand growth is represented by the USBR schedule for years 1992 to 2030, but with agricultural uses fixed at 1992 levels. The Las Vegas, Nevada, depletion is assumed to grow with projected population increases. The Central Arizona Project (CAP) depletion fluctuates over the study

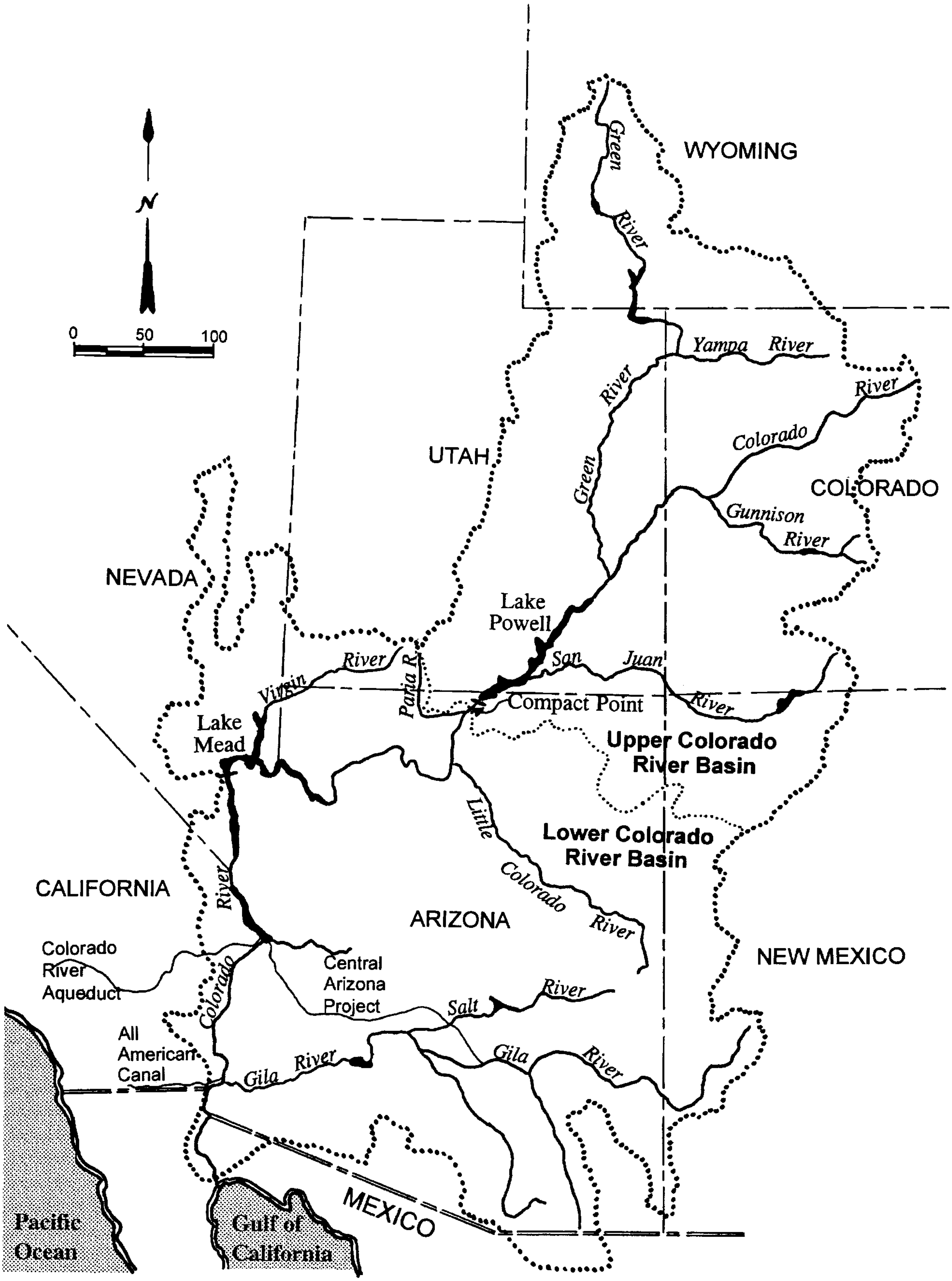

Figure 1. Colorado River Basin.

period, according to a schedule developed in the gaming exercises described by Henderson and Lord (1995).

The USBR depletion estimates on which the depletion data for this analysis are based were developed through model studies that included consideration of water supply, legal entitlement, current and expected delivery capacity, and expected development of water-using projects. Thus, they cannot be considered econometric estimates of demand for water.

DROUGHT-COPING INSTITUTIONAL RESPONSES

The three coping responses considered in this analysis and the manner in which they were implemented in the CRM are described below.

Reverse Equalization

The present equalization rule calls for releases from Lake Powell into Lake Mead to equalize the September 30 contents of the two reservoirs when certain criteria are met. Equalization is applied if: (1) the forecasted end-of-water-year (EOWY) content in Lake Powell is greater than that of Lake Mead; (2) the contents of Upper Basin federal reservoirs are greater than a certain amount – the "602(a) storage;" and (3) the Lake Mead forecasted EOWY vacant space satisfies flood control requirements. The 602(a) storage, according to section 602(a) of the Colorado River Basin Project Act (Public Law 90-537), is that quantity of storage estimated to be necessary to ensure that the Upper Basin can meet its future deliveries to the Lower Basin without impairing Upper Basin consumptive uses. Its determination is at the discretion of the Secretary of the Interior, but in current practice an equation is used (Schuster, 1987; Hydrosphere, 1994).

The reverse equalization rule evaluated here extends the equalization rule to allow for a reduction in the releases from Lake Powell into Lake Mead so as to equalize the September 30 contents of the two reservoirs. As implemented in the CRM for this study, reverse equalization is applied if the following five conditions are met: (1) the forecasted EOWY content in Lake Mead is greater than that of Lake Powell; (2) the forecasted EOWY content of Lake Powell is less than the maximum reservoir capacity; (3) the total contents of Upper Basin federal reservoirs are less than the 602(a) storage; (4) a reverse equalization minimum release equal to 34 thousand acre-feet (kaf) per month from Lake Powell can be made; and (5) the 10-year moving average release from Lake Powell should be more than 7.5 maf to satisfy the CRC delivery obligation at Lee Ferry (the fifth rule is, however, ignored in one scenario where the CRC is temporarily suspended).

Salinity Reduction

Two methods for reducing the system salinity were implemented. The first is irrigation canal lining and reduction of on-farm salt. This was implemented in the CRM by assuming that an annual reduction in salt loading at Upper Basin depletion points totaling in aggregate 1,021 kilo tons would ensue from these measures. The second method is a reduction of salt loading from natural sources. It was assumed in this case that a salt reduction of 180 kilo tons/year from the present loading of 6,474 kilo tons/year would result from measures to reduce the natural salt loading.

Minimum Streamflow Specification

The minimum streamflow levels used in these analyses were defined as the extirpation levels determined by Hardy (1995). These levels were sufficient to prevent extirpation of a population in a given reach. This was implemented in the CRM by specifying minimum flows at this level at eight river reaches within the basin, as shown in Table 1. Priorities assigned to the minimum flows in the CRM are higher than those assigned to any depletion or storage. Monthly distributions for the minimum flows were determined using the long-term average flows at these locations.

TABLE 1. Locations and Magnitudes of Specified Minimum Streamflows at the Extirpation Level.

Location	Annual Minimum Flow (kaf)
Green River Below Fontenelle	62
Green River Below Flaming Gorge	75
Yampa River Above Green Confluence	78
White River Above Green Confluence	26
Gunnison River Below Curecante	63
San Juan River Above Colorado Confluence	43
Colorado River Above Powell	458
Colorado River Below Mead	501

METHODOLOGY

The drought-coping responses were assessed by comparing three model simulations using: (1) current operating rules for the system (Baseline conditions); (2) operating rules that incorporated the drought-coping responses (Scenario 1); and (3) operating rules that incorporated the drought coping responses but suspended the CRC (Scenario 2). The two scenarios used the same depletion and SSD inflow sets as described earlier, and the same initial starting conditions. The Baseline conditions were the same as those used to simulate the SSD drought in Harding *et. al.* (1995).

Scenario 1 included three of the interstate coping responses identified in the gaming studies of Lord *et. al* (1995). The three options were what we characterize as system-wide responses – i.e., those requiring unanimous agreement among all states. Thus, water banking and marketing arrangements were not evaluated in this study. The three coping responses selected for evaluation were reverse equalization, minimum streamflow specifications, and salinity reduction programs.

The results from Scenario 1 showed that the combination of responses was not effective in mitigating substantial drought impacts in the Upper Basin. Thus, we decided to evaluate an additional coping response, suspension of the delivery requirements of the 1922 CRC. This response would be exceedingly difficult to invoke, for reasons discussed in Henderson and Lord (1995). However, we viewed it as an effective coping response when combined with reverse equalization. An arguable case can be made that article III(e) of the CRC (Meyers, 1966), which prohibits the Lower Basin from calling for water ". . . which cannot reasonably be applied to domestic and agricultural uses . . .," modifies the 75 maf, 10-year basic delivery obligation in article III(d). Under such an interpretation, no CRC call could be made until Lake Mead is empty.

The coping responses have been implemented in the CRM so as to correspond to the gaming model (Henderson and Lord, 1995) as closely as possible in scope and form, including the Central Arizona Project demands which were set to correspond as closely as possible to the amount taken by the player representing the State of Arizona. These amounts fluctuate over the study period and average 519 kaf/year.

System operations were evaluated by examining the streamflows at several locations within the basin, reservoir contents, total annual depletions of Upper and Lower Basin states, salinity, and total system hydropower generation.

In addition to testing the drought-coping responses to the severe and sustained drought hydrology, we also assessed the efficiency of the drought-coping rules when applied to "normal" and "wet" hydrologic conditions. This was done because operating rules developed in response to a drought, particularly a SSD, could be overly conservative and have unanticipated side effects when applied to normal or wet hydrologic conditions.

The Baseline and two coping scenarios were simulated in this case using the 1026-year synthetic streamflow trace divided into 27 38-year traces. The operating rules, initial conditions, and depletions used in the Baseline and two coping scenarios were used to simulate operations of the system for each of the 27 traces. The results from the three simulations using the 1026 years of synthetic streamflows were compared by examining the cumulative frequency distributions of the total annual flows at Lee Ferry and the end-of-water-year contents of Lake Powell and Lake Mead.

RESULTS WITH SSD INFLOWS

Baseline Conditions

The Baseline conditions are the same as in Harding *et al.* (1995).

Streamflows. Statistics of monthly simulated streamflows at the eight locations where minimum streamflows were specified for protecting endangered species (Hardy, 1995) are given in Table 2. A plot of simulated total annual flow at Lee Ferry is shown in Figure 2. Though the simulations were carried out with monthly time-steps, the graphs showing the results have been plotted using annual values, for clarity's sake. The total annual flow at Lee Ferry was below the 8.23 maf/yr minimum objective release required by the Operating Criteria in four consecutive years from year 19 through year 22. The CRC was invoked in year 21, but sufficient releases to comply with it were not achieved until year 26.

Reservoir Contents. Of the 14 reservoirs modeled in CRM, only the results from Lake Powell and Lake Mead are presented. The active storage capacity of these two reservoirs constitute 84 percent of the total active capacity within the system and hence account for most of the storage within the system. In addition, the storage content variation of Lake Powell is typical of the storage contents of other Upper Basin reservoirs.

TABLE 2. Modeled Monthly Streamflow Statistics at Selected Points Within the Colorado River Basin (units in thousands of acre-feet).

Station	Baseline Conditions			Scenario 1			Scenario 2		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Green River Below Fontenelle	8	626	94	8	626	93	8	626	92
Green River Below Flaming Gorge	0	810	104	3	810	103	3	772	99
Yampa River Above Green Confluence	0	773	104	2	773	105	1	773	103
White River Above Green Confluence	0	193	36	2	193	36	2	193	35
Gunnison River Below Curecante	2	719	128	6	899	128	5	899	126
San Juan River Above Colorado Confluence	0	822	101	1	822	100	1	864	97
Colorado River Above Powell	20	3,944	704	27	3,944	702	27	4,567	681
Colorado River Below Mead	245	1,006	661	245	1,006	661	245	1,006	659

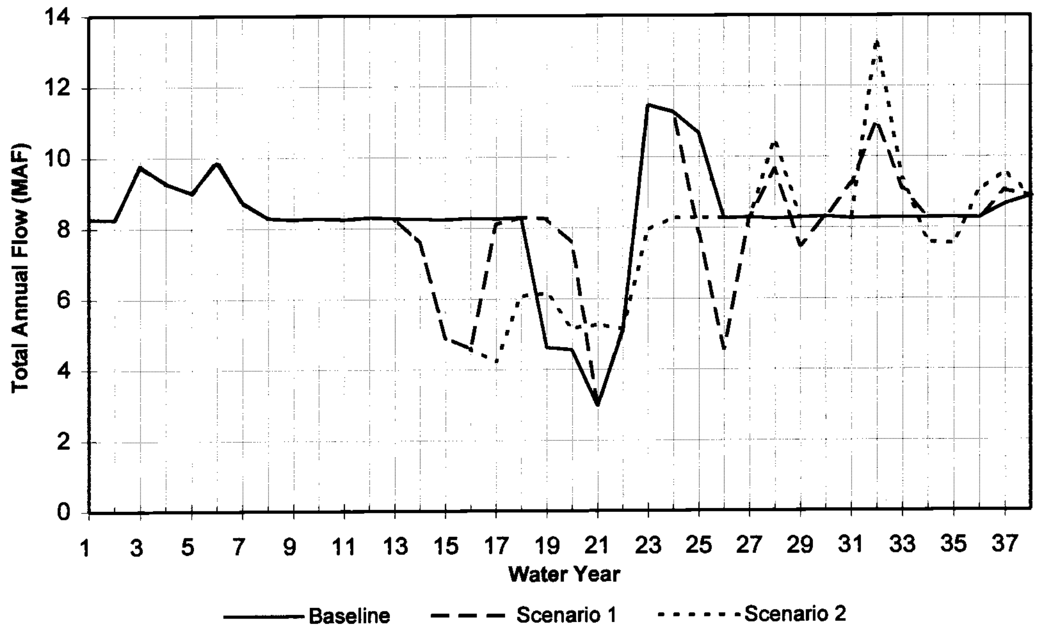

Figure 2. Total Annual Flow at Lee Ferry Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

Figure 3 shows that the active storage content of Lake Powell increased to its maximum value at the end of the fifth year and thereafter started to drop as the drought began. The active content of Lake Powell was zero by the end of year 18 and remained at dead storage for eight consecutive years. In contrast, the figure shows that the active content of Lake Mead was affected less. The lowest level at Lake Mead was 7.5 maf at the end of year 22. This sharp difference in storage contents occurred for several reasons: (a) the equalization rule resulted in releases from Lake Powell to Lake Mead above the 8.23 maf/yr minimum objective release in the first few years of the study period; (b) the minimum objective release of 8.23 maf/year from Lake Powell maintained the level of Lake Mead after the content of Lake Powell fell below that of Lake Mead; and (c) obligated deliveries from the Upper Basin through Lake Powell to satisfy the CRC continued during the worst period of the drought.

Depletions. A plot of the total annual depletion for the Upper Basin is shown in Figure 4. The total annual Upper Basin depletion is the sum of the total annual depletions for the states of Colorado, New Mexico, Utah, and Wyoming. Serious shortfalls start to occur

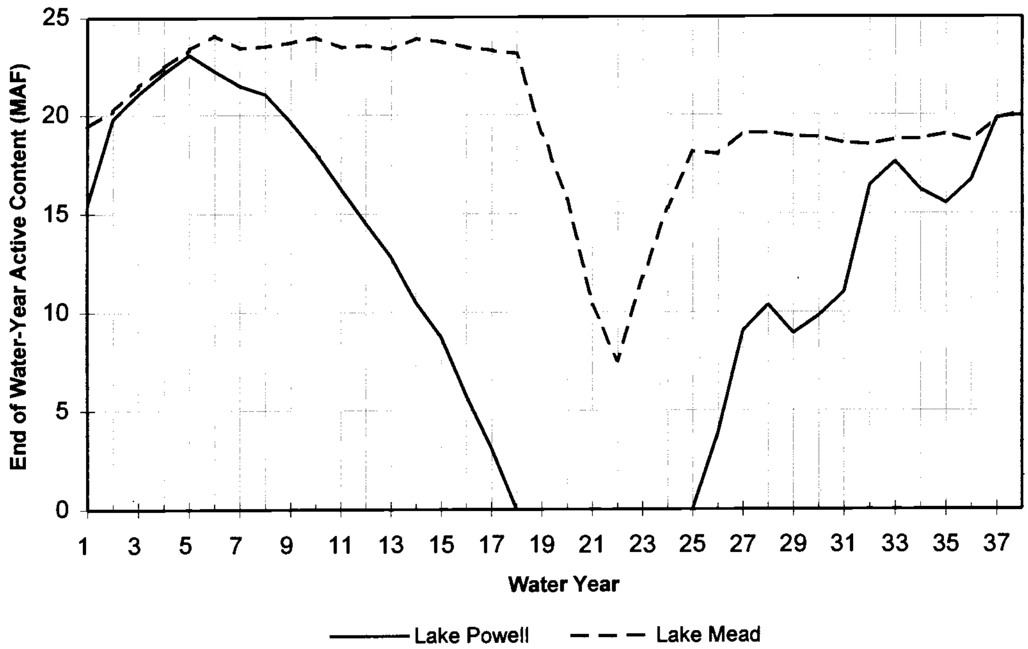

Figure 3. Lake Powell and Lake Mead End of Water-Year Active Contents Under the Baseline, with SSD Inflow Hydrology.

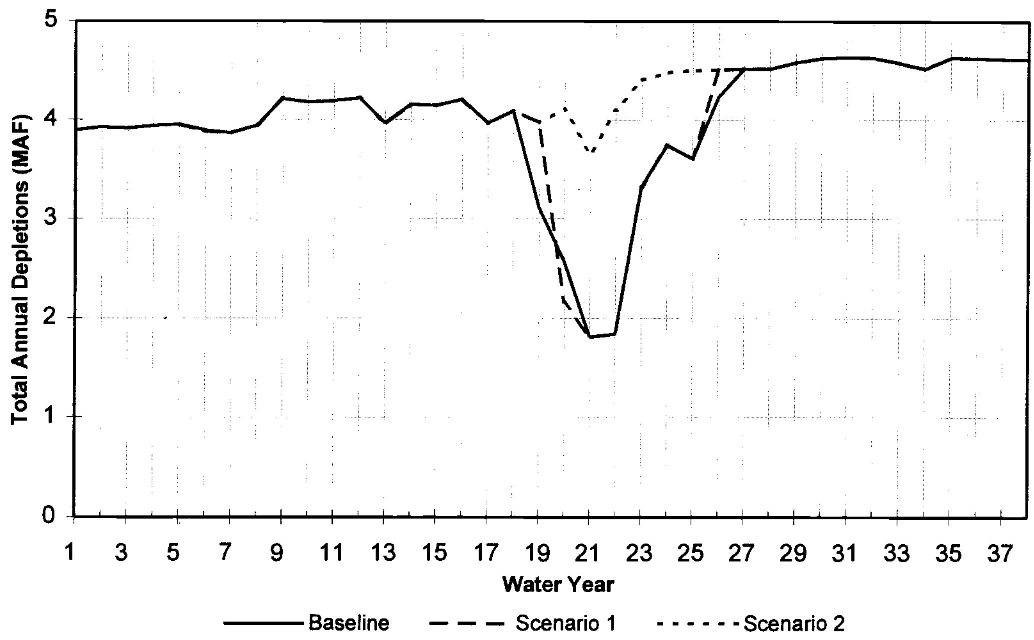

Figure 4. Upper Basin Total Annual Depletions Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

in the Upper Basin by the end of year 19 and get progressively worse thereafter. The depletion shortfall in the worst drought year, year 21, is about 59 percent.

Figure 5 shows the Lower Basin total annual depletions. The higher depletions observed in the Lower Basin in years 6 and 7 are due to surplus deliveries to California and Arizona. Slight shortfalls were observed in Lower Basin depletions in two years of the study period affecting Arizona and Nevada. However, the simulated deliveries to Mexico did not experience any delivery shortfall at any time during the study period.

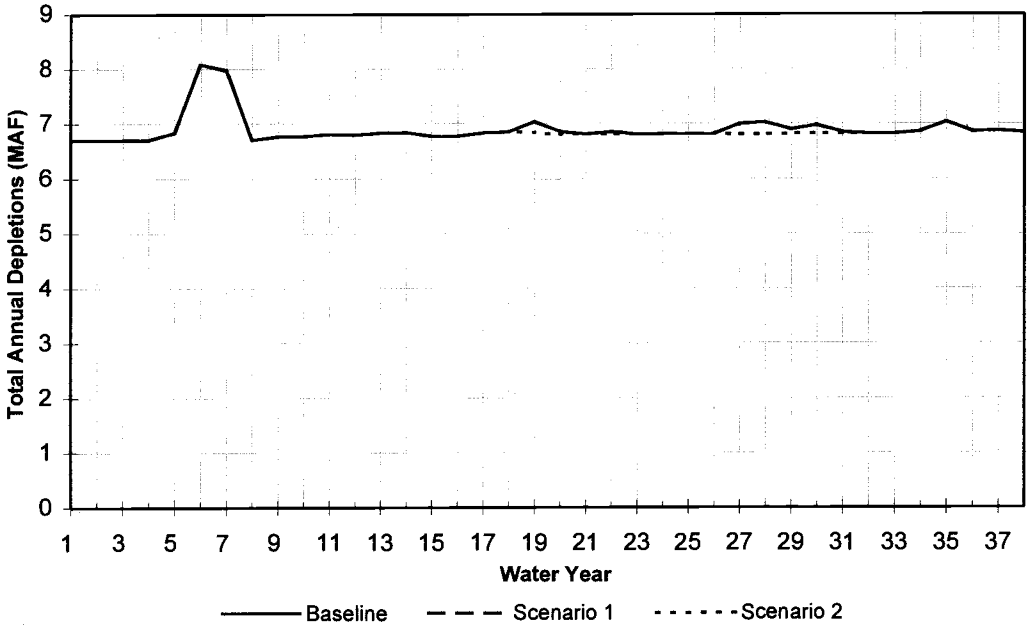

Figure 5. Lower Basin Total Annual Depletions Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

Salinity. Figure 6 shows the simulated salt concentration below Lake Mead. The salt concentration below Lake Mead increased as the drought intensified because of the smaller quantity of water available in the system to dilute the salt load. The salt concentration then receded after the drought peaked as more water was available in the system.

Hydropower. Figure 7 shows the generated energy. A rapid drop in the generated energy occurred during the worst drought years as the reservoirs started to drop below their minimum power pools.

Scenario 1

Streamflows. Statistics of simulated monthly flows at locations where the minimum streamflows were specified are given in Table 2. The table shows that the minimum flows specified as part of the drought-coping responses were complied with at all locations. The magnitude of maximum flows are about the same as in the Baseline. This is expected since maximum flows would typically occur in nondrought years where the mitigating effects of the drought-coping responses would be insignificant. The average monthly streamflows were slightly lower in the coping scenarios than in the Baseline. This shows that the drought-coping responses increased the availability of water for consumptive uses or storage.

The total annual flow at Lee Ferry dropped below the 8.23 maf/yr minimum objective release for the first time in year 14 and remained below this level for the next two years due to the effect of the reverse equalization rule (see Figure 2). However, in year 17, the CRC was invoked causing the reverse equalization to be suspended, and a release necessary to meet the CRC requirement was made. Annual releases from the Upper Basin necessary to satisfy the requirement of the CRC were also made in years 18, 19, and 20 even though the drought was intensifying and its effects were starting to become apparent in the Upper Basin. By year 21, the full release required to satisfy the CRC could not be made because of the drought severity in the Upper Basin. A similar situation also occurred in years 22 and 23 even though Upper Basin releases were increased in an effort to meet the CRC requirement. In year 26, reverse equalization was again invoked causing the total annual flow at Lee Ferry to drop to 4.57 maf. The total annual flows were subsequently increased in years 27 and 28 to satisfy the CRC.

Reservoir Contents. The active content of Lake Powell also increased to its maximum value at the end of the fifth year under Scenario 1, as shown in Figure 8, and thereafter started to drop. However, towards the end of year 14, reverse equalization was invoked and less water was released from Lake Powell in an effort to equalize the levels of Lake Powell

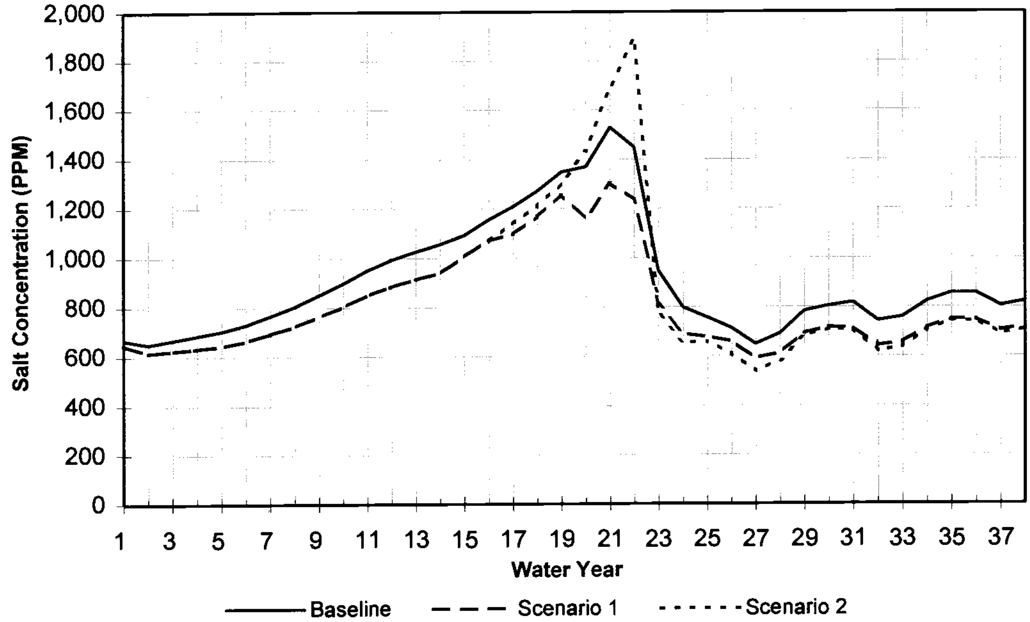

Figure 6. Salt Concentration Below Lake Mead Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

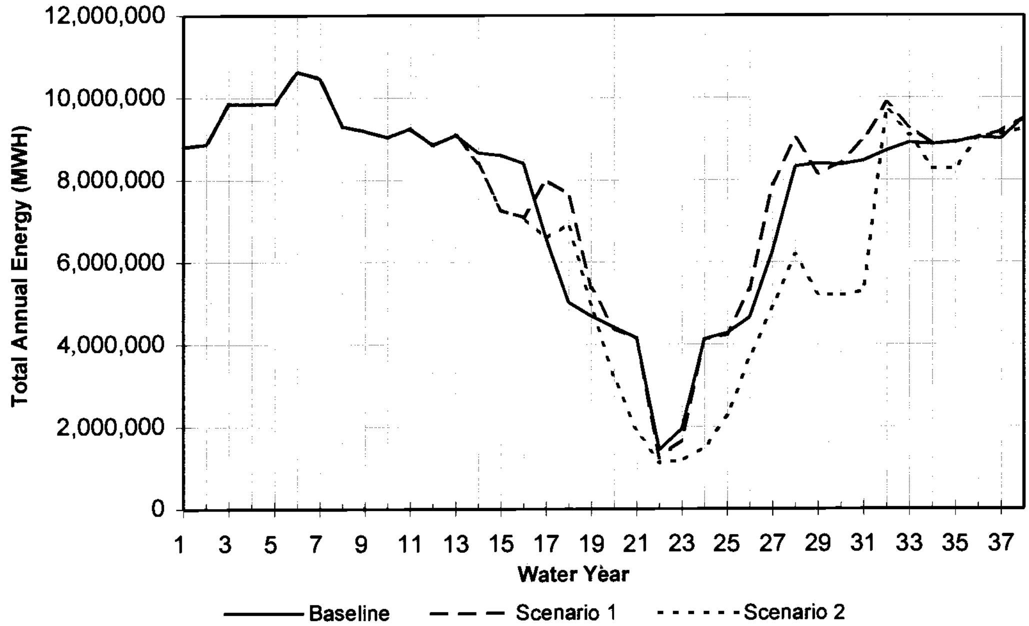

Figure 7. Total Annual System Energy Generated Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

and Lake Mead. This reduced the drawdown rate at Lake Powell and resulted in an increased drawdown rate at Lake Mead.

The reverse equalization rule continued to be in effect until year 16. Starting from year 17, reverse equalization was overridden by the CRC. Hence, releases required to achieve the CRC were initiated at Lake Powell. This had the effect of rapidly drawing down the contents of Lake Powell and other Upper Basin Reservoirs while the content of Lake Mead stabilized. By year 20, the level of Lake Powell was down to dead storage and remained there for five

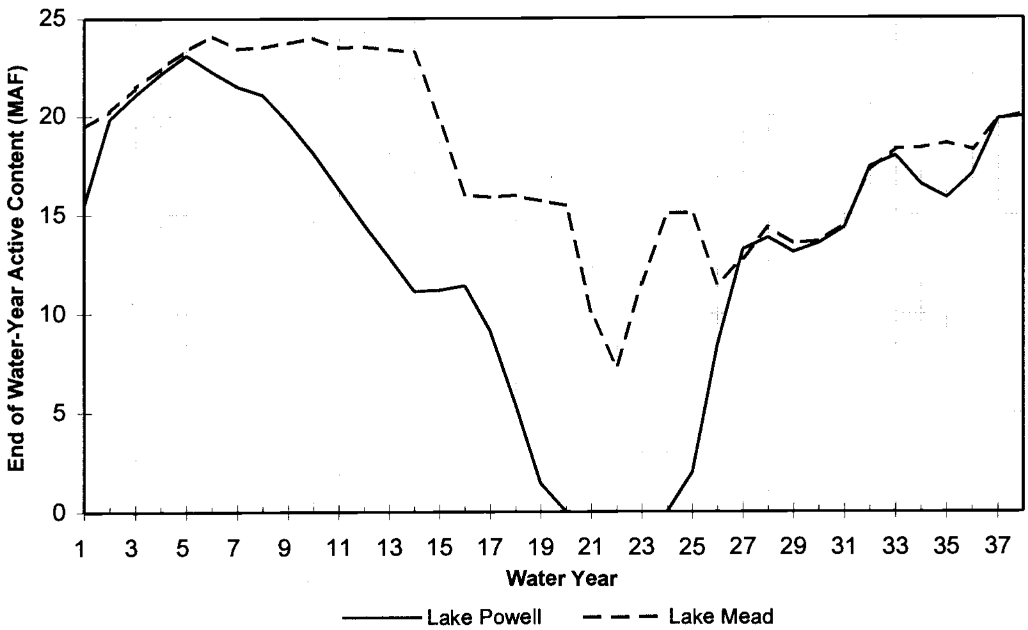

Figure 8. Lake Powell and Lake Mead End of Water-Year Active Content Under Scenario 1 (CRC Call Enforced), with SSD Inflow Hydrology.

consecutive years. The content of Lake Mead dropped sharply in years 21 and 22 because sufficient water was not released from the Upper Basin states to satisfy the CRC call due to the drought severity. Lake Mead dropped to its lowest level of 7.5 maf in year 22, the same as in the Baseline. After year 22, the content of Lake Mead rose rapidly until year 24 because releases necessary to satisfy the CRC were being made from the Upper Basin as the drought started to subside. In years 25 and 26, the reverse equalization rule was again invoked without violating the 7.5 maf 10-year average delivery requirement at Lee Ferry, and the contents of Lake Powell and Lake Mead were equalized by the end of year 27.

Depletions. Figure 4 shows that Upper Basin depletion shortfall was not manifest in Scenario 1 until the end of year 20, at which point it is more severe than the depletion shortfall in the Baseline. The depletion shortfall was delayed for one year because of the implementation of reverse equalization. When it did occur, it was more severe than in the Baseline because of the higher release required to satisfy the CRC after reverse equalization was discontinued. Depletion shortfalls in subsequent years were almost as severe as in the Baseline since the coping response that could mitigate the depletion shortfall (i.e., reverse equalization) had been overridden.

Figure 5, which shows the simulated total annual depletions for the Lower Basin, shows that there were no differences in Lower Basin depletion levels between Scenario 1 and the Baseline. The simulated deliveries to Mexico also did not experience any shortfall at any time during the study period.

Salinity. Figure 6 shows the simulated salt concentration below Lake Mead. The figure shows that the salt concentration below Lake Mead is lower than in the Baseline throughout the study period. This is because of the salinity reduction program implemented as a coping response to reduce salt loading through on-farm efficiencies and natural salt load reductions. The peak of the salt concentration was 15 percent lower than the peak under the Baseline conditions.

Hydropower. Figure 7 shows the energy generated under this scenario. Of the three scenarios, the most energy was generated under Scenario 1 because the amount of the time Lake Powell and Lake Mead were below the minimum power pools was less.

Scenario 2

Streamflows. Statistics of simulated monthly flows at locations where minimum streamflows were specified are given in Table 2. The table shows that the minimum flows specified as part of the drought-coping responses were complied with most of the time at all locations.

The total annual flow at Lee Ferry dropped below the minimum objective release of 8.23 maf/yr for the first time in year 14 (see Figure 2). The drop occurred because of the reverse equalization rule. The total annual flow then remained below the 8.23 maf/yr level for 10 consecutive years starting from year 14. This was allowed to happen because the CRC, which would have required the total annual flows to be increased in order to satisfy the mandated 7.5 maf 10-year delivery requirement, was suspended in this scenario.

Reservoir Contents. There were no differences between the reservoir contents under this scenario and in Scenario 1 for the first 16 years of the study period (see Figure 9; compare to Figure 8). As in Scenario 1, reverse equalization was invoked towards the end of year 14 and was still in place by year 16. However, unlike the Scenario 1, reverse equalization continued to be invoked until year 23.

Because the reverse equalization rule was not overridden in this scenario, its effect in mitigating the drought impact on Upper Basin reservoir contents was more noticeable, as shown in Figure 9. The rule kept the content of Lake Powell to be almost equal to that of Lake Mead throughout the drought period. Reverse equalization resulted in the rapid drawdown of Lake Mead starting towards the end of year 14, such that the content of Mead dropped from 23.24 maf by the end of year 14 to 12.08 maf by the end of year 17, at which point it was almost equal to the content of Lake Powell for the first time. The reverse equalization rule also decreased the drawdown rate of the Upper Basin reservoirs when compared to the Baseline or Scenario 1.

The contents of Lake Powell and Lake Mead continued to fall at about the same rate from year 17, such that by the end of year 22, Lake Powell was empty and Lake Mead was almost empty. The active content of Lake Powell was zero in only one year under this scenario. After the drought peaked, the content of Lake Powell recovered faster than that of Mead, such that by the end of year 27, Lake Powell was much higher than Lake Mead and the total content of Upper Basin reservoirs was more than the 602(a) storage level. This invoked the equalization rule in year 28, causing releases from Lake Powell above the 8.23 maf/yr minimum objective release requirement in order to equalize the contents of Lake Mead and Lake Powell (see Figures 2 and 8). A similar situation also occurred in years 32 and 33. Lake Mead contents were below the elevation of the Southern Nevada intakes (1050 feet msl, corresponding to 7.26 maf) for a period of eight years in Scenario 2.

Depletions. Depletion shortfalls in the Upper Basin under Scenario 2 were substantially reduced compared to the first two scenarios. This is because reverse equalization was implemented throughout the severe drought period and because suspension of the

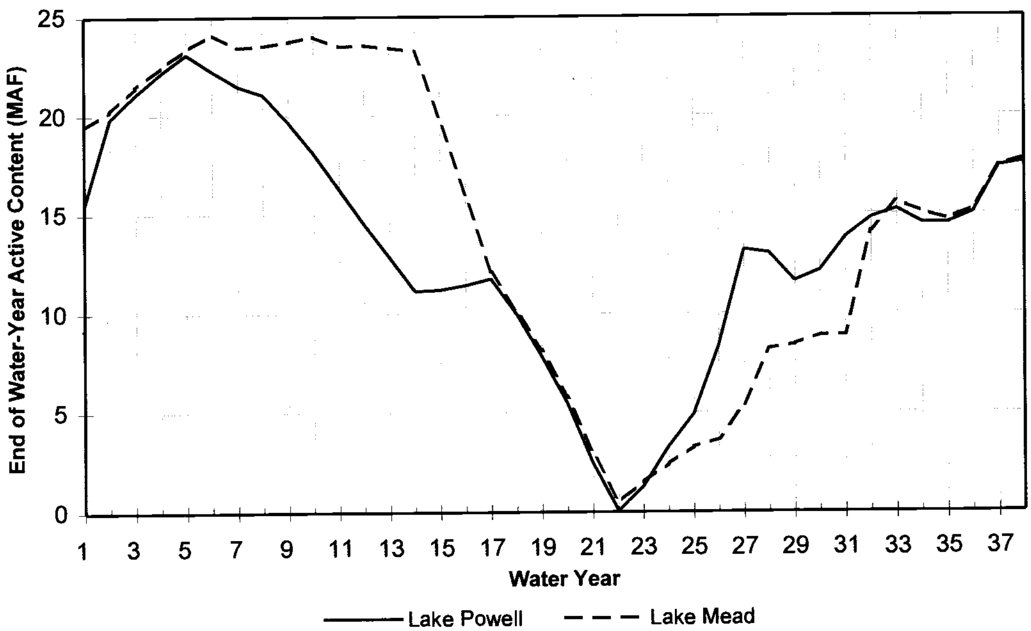

Figure 9. Lake Powell and Lake Mead End of Water-Year Active Content Under Scenario 2 (CRC Call Suspended), with SSD Inflow Hydrology.

CRC eliminated the need to bypass flows when Lake Powell did empty. Hence, more water was kept in Upper Basin reservoirs which were then available for consumptive uses. In the worst year of the drought, year 21, the depletion shortfall in the Upper basin under Scenario 2 was only 18 percent compared to a depletion shortfall of 59 percent under the Baseline and Scenario 1 (see Figure 4).

Lower Basin depletion shortfalls to CAP and Nevada were more under this scenario than in the Baseline and Scenario 1 (see Figure 5). Note that we assumed that Nevada took the necessary measures to continue pumping from Lake Mead after the reservoir level dropped below the existing intake elevation. California depletions were unaffected compared to the Baseline conditions. The shortfalls to CAP and Nevada occurred because reverse equalization, which was in place throughout the drought period, resulted in the drawdown of Lake Mead below its shortage elevation (which corresponds to a reservoir content of 10.762 maf). When the content of Lake Mead falls below the shortage elevation, a shortage is declared, the CAP deliveries are cut back to a minimum annual delivery of 450 kaf/yr, and a shortfall equal to 4 percent of the CAP shortage is imposed on Nevada. The content of Lake Mead dropped below the shortage elevation for the first time in year 19 and remained below the shortage elevation until year 31. Years without depletion shortfalls in this period corresponded to those years when the CAP demand was equal to the minimum 450 kaf/yr. Note that Lake Mead did not empty in this scenario, so it was not necessary to bypass water at Upper Basin diversion locations. Simulated deliveries to Mexico also did not experience any shortfall at any time during the study period.

Salinity. The simulated salt concentration below Lake Mead started off lower compared to the Baseline, at the same level as in Scenario 1 (see Figure 6). However, starting from year 16, the salt concentration increased at a higher rate and was actually higher than in the Baseline in three of the worst drought years in spite of the fact that the salinity reduction program was still being implemented. This is a result of higher depletions in the Upper Basin. The higher depletion rate in the Upper Basin increased the salinity in two ways: (1) by introducing salt into the system from the salt load associated with the depletions; and (2) by decreasing the amount of water in the system available to dilute the salt load. After the worst drought years, the salt concentration below Lake Mead then fell to a level comparable to that under Scenario 1 due to the effect of the salinity reduction programs. The peak of the salt concentration was 24% higher in Scenario 2 than the peak of the salt concentration in the Baseline.

Hydropower. Figure 7 shows the generated energy. A rapid drop in the generated energy also occurred during the worst drought years as the reservoirs started to drop below their minimum power pools. The least amount of energy was generated in this scenario because the reservoirs spent more time below the minimum power pool.

RESULTS UNDER NORMAL HYDROLOGIC CONDITIONS

Drought-coping responses identified as effective in mitigating the effects of an SSD might be overly conservative in normal and wet periods. We examined the cumulative frequency distributions of simulated annual flows at Lee Ferry and reservoir contents of Lake Powell and Lake Mead for the Baseline conditions and two drought-coping scenarios.

The differences between the cumulative frequency distributions of simulated total annual flows at Lee Ferry of the two coping scenarios and that of the Baseline are not significant. Over the middle range flows, between 28 and 70 percent non-exceedence, the frequency distributions of the three simulations are close. The frequency distributions for the coping scenarios are lower than the frequency distributions for the Baseline in the lower flow range (between the 1 and 18 percent non-exceedence values), which is consistent with observations from the simulations where we used the SSD inflows. The cumulative frequency distributions for the coping scenarios are higher in the higher flow ranges, between the 71 and 96 percent exceedence levels. Above the 96 percent exceedence level, the frequency distributions are almost equal. This implies that the coping scenarios induce slightly higher annual flows at Lee Ferry than the Baseline during wet years because Upper Basin reservoir contents are higher, but the there is virtually no difference in the simulated flows at Lee Ferry in extreme flow years since the reservoirs will be spilling in all scenarios.

The cumulative frequency distributions of Lake Powell storage for the coping scenarios are higher than that of the Baseline over the 1 to 64 percent nonexceedence range. Above the 64 percent nonexceedence level, all the curves are quite close. The cumulative frequency distributions for Lake Mead end-of-year storage content for the coping scenarios are lower than that of the Baseline over the 1 to 68 percent nonexceedence range. Above the 68 percent nonexceedence level, all the curves are quite close. These results show that the drought-coping responses tend to keep the reservoirs at higher levels during dry and normal conditions, but the drought-coping responses have very little effect on reservoir storage contents under wet conditions.

SUMMARY AND CONCLUSION

The drought-coping responses evaluated in this study successfully mitigated some of the impacts of the severe and sustained drought on depletions in the Upper Basin, with only slight impacts on consumptive uses in the Lower Basin. Imposition of a minimum streamflow requirement was successful in maintaining specified minimum streamflows throughout the drought, with no apparent effect on consumptive uses. The impacts of the coping responses on other system variables were not as clear cut.

Scenario 1 provided no benefit in terms of depletions, but it improved (over the Baseline conditions) minimum streamflows, energy production and salinity. Reservoir contents were increased modestly in the Upper Basin in Scenario 2 but at the inevitable cost of corresponding reductions in Lower Basin storage. The reverse equalization rule was ineffective in mitigating drought effects because it could only maintain Lake Powell contents temporarily in the face of the CRC delivery obligation. Because of the ten-year scope of the CRC delivery obligation, reduced flows in years 14, 15, and 16 were recaptured in years 19 and 20. These results led us to evaluate the additional coping response of suspension of the delivery obligation of the CRC.

Scenario 2 provided significant benefits in reducing depletion shortfalls in the Upper Basin, with only a slight increase in shortfalls in the Lower Basin. Minimum streamflows were maintained at the specified levels. Salinity conditions and energy production were worse than both the Baseline conditions and Scenario 1 because the coping response allowed additional depletions in the Upper Basin compared to the Baseline and Scenario 1. Reservoir contents were increased in the Upper Basin, but with significant reductions in the Lower Basin. This was the only scenario in which Lake Mead dropped below the elevation of the Southern Nevada Intake.

It is important to note that the accounting of shortfalls reported in the Lower Basin in this study do not include interruption of "surplus" deliveries to California – specifically the Metropolitan Water District (MWD). While these supplies, which have been provided historically, are most commonly referred to as "surplus" deliveries, they can more accurately be described as temporary delivery of unused entitlements. The supplies provided to MWD historically were not "surplus" to fully-developed entitlements, and their expected frequency is greatly reduced now that CAP has begun to take water from the river. Thus, the inability of the system to deliver the so-called surplus supplies to MWD cannot be considered to be a result of the drought. Rather, it is a result of a chronic water shortage and should be addressed as such and not as the object of drought-coping measures.

Assessment of the drought-coping rules under hydrologic conditions representative of long-term conditions indicate that the rules would have relatively inconsequential effects on the operation of the system during normal and wet years.

ACKNOWLEDGMENTS

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MANAGING THE COLORADO RIVER IN A SEVERE SUSTAINED DROUGHT: AN EVALUATION OF INSTITUTIONAL OPTIONS[1]

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ABSTRACT: This paper presents a summary of the findings and recommendations of the studies of severe, sustained drought reported in this special issue. The management facilities and institutions were found to be effective in protecting consumptive water users against drought, but much less effective in protecting nonconsumptive uses. Changes in intrastate water management were found to be effective in reducing the monetary value of damages, through reallocating shortages to low-valued uses, while only water banking and water marketing, among the possible interstate rule changes, were similarly effective. Players representing the basin states and the federal government in three gaming experiments were unable to agree upon and effect major changes in operating rules. The conclusions are (1) that nonconsumptive water uses are highly vulnerable to drought, (2) that consumptive uses are well-protected, (3) that drought risk is greatest in the Upper Basin, (4) that the Lower Basin suffers from chronic water shortage but bears little drought risk, (5) that opportunities exist for win-win rule changes, (6) that such rule changes are extremely difficult to make, and (7) that intrastate drought management is very effective in reducing potential damages.
(KEY TERMS: drought; water policy; water institutions; Colorado River; systems analysis.)

INTRODUCTION

The Colorado River is one of the most highly controlled and most intensively utilized river systems in the world. Two large federal reservoirs, Lake Mead and Lake Powell, are capable of storing nearly four times the mean annual flow of the river. Smaller reservoirs, both federal and non-federal, add additional storage and hydroelectric power generation capacity. Transbasin diversion facilities divert Colorado River water to Southern California, Eastern Colorado, Western Utah, and Eastern New Mexico. In most years, the flow of the river is so intensively utilized that none discharges into the Gulf of California, its outlet to the sea.

The "Law of the River" is the term often used to refer to the existing complex of Colorado River water allocation and management rules contained in two interstate compacts, one international treaty, several acts of Congress, and the operating criteria for system reservoirs promulgated by the Department of the Interior. This complex of rules for operating the basin's "plumbing system" has evolved over more than 70 years (as has the system itself), but its ability to cope with a severe sustained drought has never been tested. Such a drought could produce hydrologic and social stresses far greater than those experienced in more normal periods. Droughts more severe than those of the last hundred years have occurred in the more remote past, and they will surely occur again in the future.

Investigators from several Colorado River Basin states have been engaged for about a decade in a major program of research designed to evaluate the capability of the region's water management structures and institutions to cope with a severe sustained drought (SSD). This research program has included the following: tree ring reconstructions of historic runoff conditions; hydrologic analyses of the probability distribution of river flows; engineering simulations of the functioning of the water management facilities and institutions under various runoff scenarios; legal and other institutional analyses of current interstate water allocation rules, and possible changes in them; studies of potential environmental impacts of different hydrologic scenarios; economic projections of

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water-related benefits and costs of such scenarios; explorations of the social impacts of drought in the basin states; and a gaming experiment in changing rules for managing the system as the drought progresses.

The methods and findings of all of these studies are described in companion papers to this one. Our purpose here is to provide a synthesis of the findings from all of these studies which bear upon future management of the system, to highlight their implications, and to provide policy recommendations based upon those implications.

Our findings, conclusions, and recommendations derive largely from our computer simulations of the behavior of the physical-institutional water management system when subjected to the stress of a 38-year severe drought, a drought resembling one which occurred late in the sixteenth century, and the most severe drought which presently available technology allows us to identify. These findings, conclusions, and recommendations fall into three groups: those which pertain to the existing operating rules (the Law of the River); those which pertain to potential changes in the existing rules; and those which pertain to the feasibility of making such changes (through negotiation, legislation, or litigation).

FINDINGS

Drought Performance of the Law of the River

The SSD hydrologic models predict that, under present institutional arrangements (the Law of the River), Lake Powell and other major Upper Basin reservoirs would be emptied, and Lake Mead nearly so, after two decades of severely reduced runoff. Water deliveries for consumptive uses in the Upper Basin would fall to about half of normal levels, *albeit* for only a few years. Consumptive uses in the Lower Basin would be largely unaffected, save for those served by the Central Arizona Project. Until recently, California was able to use about a million acre-feet of Colorado River water annually beyond its regular compact entitlements. After the completion of the Central Arizona Project canal, such "surplus" usage is unlikely to recur reliably, and we do not include chronic inability to divert this surplus as a drought-caused shortage. In all, basin-wide shortages would be less than 25 percent of normal demands, even at the depth of the drought (Harding *et. al.*, 1995). California, in its recent droughts, has coped with more severe shortages.

So-called instream, or nonconsumptive, water uses (hydroelectric power generation, water-based recreation, environmental protection, and salinity control) would fare less well. Predicted power generation declines during the low flow years and would cease altogether at the depth of the drought. Water-based recreation at Lakes Mead and Powell and at five other system reservoirs would decline with decreasing water levels in those reservoirs. Instream flows would be inadequate at times for the survival of some endangered species at some locations. Riparian wetlands would be seriously affected. Salinity levels in drinking and irrigation water would rise to levels higher than experienced since the completion of Hoover Dam.

The single largest predicted economic impact of the drought was the loss of electricity, with an average value of 600 million dollars annually. Reductions in water deliveries to municipal, industrial, and agricultural users would also be substantial, and benefits to those users would be significantly reduced due to salinity increases. Recreational benefits would fall by lesser but still appreciable amounts. Lower Basin states would experience minimal losses to consumptive water uses but would suffer major losses to nonconsumptive uses. Just the opposite was true of the Upper Basin states. The estimated present value of discounted economic damages, excluding salinity, for the entire drought was $5 billion, only 45 percent of which was to consumptive uses (Booker, 1995). To say that nonconsumptive uses would sustain 55 percent of the drought damages is an understatement because it ignores both salinity and nonmonetary damages, such as extirpation of endangered species. Both local extirpations of endangered species and loss of wetlands occurred as a result of the drought and may have been aggravated by management measures taken to protect consumptive uses. Most instances of environmental deterioration are to some degree reversible. In the case of threatened and endangered species, however, losses are not so easily reversible. Complete extinction of a species is clearly irreversible, but localized extirpations are probably reversible, given enough time and effort, provided that breeding stocks exist elsewhere in the system. Localized extirpations were predicted in Flaming Gorge, Navajo, and Lake Powell reservoirs, and in the Green River below Flaming Gorge. All of the reservoir extirpations were eventually reversed, but that in the Green River was not (Hardy, 1995).

Drought Performance of Alternative Operating Rules

Several potential revisions to the Law of the River were formulated and evaluated, both by SSD institutional researchers and by those who participated in the gaming experiment. Among these changes were (1) adoption of a reverse equalization rule, which would tend to maintain similar water levels in Lakes Mead and Powell (the existing equalization rule protects Mead at the expense of Powell); (2) temporarily ignoring the Upper Basin's delivery obligation to the Lower Basin to avoid Upper Basin shortages at times when no shortages were imposed upon the Lower Basin (in effect sharing system-wide shortages proportionally among the basin states); (3) revising reservoir operating rules to store water in headwaters reservoirs as long as possible (thus minimizing evaporative losses); and (4) permitting water banking and marketing between states, so long as no other states were harmed thereby (Booker, 1995; Henderson and Lord, 1995; MacDonnell *et al.*, 1995).

Changes in water allocation and management rules within basin states were also considered. In general, these changes took the form of proportional sharing of shortages or water marketing, under which water was transferred from senior agricultural rights to junior municipal rights, something which was not permitted under the base line analysis representing existing institutions. Responses in Arizona were more complex, however, reflecting that state's several options for managing its allocation of Central Arizona Project (CAP) water (Henderson and Lord, 1995).

Two types of changes in the Law of the River could provide major reductions in overall losses. Changing the Law of the River to require water to be stored high in the basin, thus minimizing reservoir evaporation, could reduce drought damages by about one fourth. Equally effective were intrastate and interstate water banking and water marketing because they allowed Arizona to transfer CAP water, the agricultural use of which would otherwise require subsidization, to municipal uses in the other Lower Basin states. Otherwise, changes in the Law of the River were not very effective in mitigating drought damages. However, changes which would reduce consumptive uses further, with the intent of mitigating damages to nonconsumptive uses, remain to be explored (Booker, 1995).

Changes in intrastate water allocation and management were more effective in mitigating drought damages than were those changes in the Law of the River which we analyzed. In particular, transferring water from low-valued agricultural uses to higher-valued municipal and industrial uses shows considerable promise. Such reallocations did occur in the recent California drought and have long been observed in Colorado. Indeed, reducing agricultural water use during drought could go beyond preventing shortages to higher-valued municipal uses and could also partially sustain nonconsumptive uses, such as hydropower, recreation, and environmental protection. Our studies showed that the gains from managing system reservoirs to maintain hydropower production would outweigh concomitant consumptive water use damages if those damages were suffered only by agriculture. Shorting consumptive uses is most effective if concentrated in the Upper Basin because more downstream nonconsumptive uses can benefit (Booker, 1995; Henderson and Lord, 1995), so measures that redistribute shortages away from the Upper Basin for reasons of increased equity would increase the system-wide damages from the drought.

Despite the mostly temporary extirpations, there was a net improvement in conditions for the four threatened and endangered species whenever the operating rules were interpreted to include invoking the Endangered Species Act to modify reservoir release rules and protect these species whenever it appeared to be necessary. To do so, of course, causes some reduction in water deliveries for offstream consumptive uses to the Upper Basin.

Institutions for Changing Operating Rules

The kinds of changes in the Law of the River which were explored in this research can be accomplished in several different ways, as is shown by the history of the evolution of that institution. The first way is by interstate negotiation. This is how the two interstate compacts were formulated. The second way is by federal legislation. This is how the major reservoirs were constructed and how the 1922 Upper Basin-Lower Basin apportionment was originally put into effect. The third way is by judicial decision, as represented by the far-reaching 1968 decree in Arizona v. California. The fourth way is by administrative rule-making, represented by the promulgation of the Interior Secretary's operating criteria for Hoover and Glen Canyon dams (Henderson and Lord, 1995; Kenney, 1995; MacDonnell *et al.*, 1995).

Our studies suggest that institutions which possess (1) sufficiently broad responsibility and authority to deal with all interrelated problems, (2) provide for appropriate representation and participation of all major affected interests, (3) generate and distribute objective and technically sound information, and (4) facilitate communication and bargaining between states are most likely to adopt and implement operating rules which resolve conflict and achieve efficient and equitable resource allocation. The single federal administrator model which is predominant in the complex of existing collective choice institutions in the Colorado River Basin largely fails to meet these criteria (Kenney, 1995).

Our gaming experiment placed players acting as representatives of the seven basin states and the federal government in three collective choice situations where they were required to agree upon changes in the Law of the River in order to mitigate drought impacts. In essence, each of these situations was governed by rules which were variants of the interstate negotiation model. The participants achieved only minor rule changes, and even less substantial mitigation results, perhaps due to perceived restrictions in the scope of their responsibilities and to information deficiencies. They were most successful when permitted to engage in bilateral water banking and water marketing transactions. Their greatest achievements in reducing drought damages resulted from the intrastate water management changes which they were able to make independently (Henderson and Lord, 1995).

IMPLICATIONS

Nonconsumptive Water Uses Are Highly Vulnerable to Drought

Existing operating rules and those changes which we examined favor consumptive water uses over such nonconsumptive uses as hydroelectric power generation, environmental protection, salinity control, and recreation. The extent of this favoritism (technically, the tradeoff ratio) is out of all proportion to what are, arguably, the public values involved. This conclusion emerges even when such nonmonetary values as environmental protection are discounted completely. It is even stronger if reasonable weight is given to these nonmarket factors.

Both absolute and relative declines in the monetary values of nonconsumptive water uses are far greater than is true for consumptive uses, taken as a whole. In other words, the nonconsumptive uses are far more vulnerable to drought than are consumptive water uses, at least when the system is managed pursuant to current rules or pursuant to the variants on those rules which we examined.

Hydropower is seen to be highly vulnerable to the representative severe sustained drought. However, this is not to say that drought-caused losses could be avoided through adopting different water management institutions, as was largely possible in the case of consumptive water uses. Because there is less inflow in drought years, there is bound to be less hydropower generation, even if all withdrawals for consumptive uses were to cease. However, by sustaining withdrawals for consumptive uses (especially in the Upper Basin) above levels which would have characterized an unmanaged drought, the Colorado River management system substantially increases the severity of drought-related hydropower losses.

Monetary losses to hydropower, recreation, and water quality are not the only damages suffered by nonconsumptive water uses. Endangered species, wetlands, and other environmental attributes are also affected adversely.

Consumptive Water Uses Are Well Protected from Drought

The severe sustained drought does produce damages or losses to consumptive water users (farmers, industries, and municipalities), even if only in the Upper Basin, and there only for a few years. A substantial drop in water deliveries to consumptive uses occurred when the drought was at its worst. However, when states managed their intrastate waters efficiently, the drop in monetary benefits was much smaller, in relative terms, than was the shortage which produced that drop (Booker, 1995; Henderson and Lord, 1995).

The players in the three drought managment games did not act effectively to limit drought-caused losses to nonconsumptive water uses, even though it appears that the opportunity costs associated with such mitigation, in the form of increases in losses to consumptive uses, would have been less than the benefits to be achieved. We believe (without direct evidence to confirm this belief) that the players, in attempting to simulate the behavior of state engineers and other state water decision makers, focused overwhelmingly upon their ability to achieve the diversions of Colorado River water which were their presumed entitlements under the Law of the River. In so doing, they overlooked other factors which might be thought important to interests which were neither directly (nor even indirectly) represented in our experiments. In reality, of course, environmental, recreational, and, especially, energy interests would be expected to exert considerable political influence to protect their own presumed entitlements, and would have ample time and channels to do so in the course of a sustained drought. The potential effectiveness of such efforts is another matter.

Drought Risk Is Greatest in the Upper Basin, But in Normal Years Supplies Are Abundant

The 1922 Colorado River Compact essentially gives the Lower Basin states seniority in claiming the first

7.5 million acre-feet of Colorado River flows, although it is often held that half of the delivery obligation to Mexico must come out of that allotment. Only after the full Lower Basin obligation has been met can the Upper Basin states begin to satisfy their rights administered under the compact. Thus, the Lower Basin has a legal right to at least the first 6.75 million acre-feet of water flowing in the Colorado, after the Upper Basin present perfected rights of approximately 2.2 million acre-feet have been satisfied. This Lower Basin priority effectively transfers all of the drought risk to the Upper Basin.

In normal times, the Upper Basin share may be expected to amount to about 5.5 million acre-feet (including present perfected rights, and depending upon what one takes to be the mean annual flow of the river, itself an ambiguous concept when referring to a nonstationary time series like this one). Current Upper Basin depletions amount to over four million acre-feet annually (including present perfected rights). Therefore, at the present level of development, the Upper Basin uses far less than its entitlement as long as runoff is near normal.

The Lower Basin Suffers Chronic Water Shortages But Bears Little Drought Risk

California could be said to be in a state of chronic water shortage, but at current demand levels it and the other Lower Basin states are virtually immune to a Colorado River Basin drought. By the 1922 compact agreement, the Lower Basin gained the assurance of a stable water supply at the expense of limiting its long-term mean withdrawals to less than the amount needed to meet its potential demands. Conversely, the Upper Basin states gained a long-term limitation on the Lower Basin's share of the system yield, at the cost of assuming almost the entire drought risk of the entire basin. From a drought protection standpoint, and considering only consumptive water uses, the Lower Basin states enjoy a remarkably superior position to that of the Upper Basin. By the same token, the price paid for that advantage has been high, both in terms of foregoing greater long term access to normal flows and in terms of impacts upon non-consumptive water uses (these impacts bear most heavily upon the populous Lower Basin).

Opportunities Exist for Win-Win Rule Changes

Existing operating rules needlessly limit California's long-term water supplies while needlessly increasing the upper basins' vulnerability to short-term drought. It would be relatively inexpensive for the Upper Basin and Arizona to reduce their long-term claims upon Colorado River water in order to enable California to meet demands which already exist. It would be similarly inexpensive for California to agree to share the burden of accommodating future drought shortages more equally, thus relieving what could be traumatic shortages in Upper Basin states, particularly Colorado. This finding suggests a possibility for grasping that most desirable of conflict resolution possibilities, the positive-sum solution in which there are only winners and no losers.

Existing decision-making institutions for interstate water allocation and management are designed to resolve conflicts between states acting exclusively in their own self-interests. They are not designed for discovering what the collective or common interest may be, unless that common interest is taken to comprise only resolution of such interest conflicts. Still less are they designed to facilitate action in the common interest, should it be revealed.

Only Minor Changes Can Be Made Under Existing Rules

The SSD gaming experiments were conducted within the limited context of those changes in interstate water allocation (operating rules) which institutional specialists believed to be attainable without changes in statutes or judicial interpretations. The gaming was conducted under collective choice rules which approximate those currently in effect and then was repeated twice, each time under a modified set of operating rules but, again, including only those changes which were thought to be attainable without legislative or legal action.

The most striking aspect of the outcomes of the three SSD drought gaming exercises is their similarity. The players simply were unable to change those outcomes very much through negotiating changes in the operating rules, even though a great deal of communication occurred in both the second and third games, and many water transfer deals were successfully struck in the third game.

The players employed a very narrow set of decision criteria throughout all of the games. We believe that the players attempted almost single-mindedly to maximize Colorado River water deliveries to their respective states, within and up to the limits of their compact entitlements. We further believe that, with the exception of the equalization rule, the existing operating rules are hard to improve upon, from the limited perspective of coming as close as is possible to fulfilling compact entitlements.

Intrastate Drought Management is Most Effective

Two state players, those representing Arizona and Wyoming, were more successful in managing drought, at least by some criteria, than were most others. The Arizona player was able to reduce Arizona's demand for consumptive uses of Colorado River water progressively, from 2-1/2 to under 2 million acre-feet annually as he played the three games, while at the same time virtually eliminating drought-caused water shortages. In doing so, he was able to reduce drought-related monetary losses to his state by $23 million, on an average annual basis (the reduction was much greater for the worst drought years). His success was due to his astute *interstate* water marketing transactions in the third game, coupled with his choice of *intrastate* water management rules, including conjunctive management of surface and groundwater resources, which were consistent with them.

The Wyoming player in the first game was able to achieve significantly higher water-related net benefits than the (different) player in the third game, despite the fact that Wyoming demand (for consumptive uses), supply (diversions), and shortages were identical in both games. That player also achieved a higher level of benefits than did the (different) player in the second game, even though the player in the second game was able, acting in concert with the other players at the collective choice level, to adopt a reverse equalization rule and thereby reduce upper basin shortages appreciably.

The reason for the difference is that the player in the first game selected a change in intrastate water allocation rules which enabled free marketing of water between agriculture and municipalities. The resultant drought-year leases increased benefits to both farmers and municipalities, and constituted a more effective drought management strategy, from a monetary perspective at least, than Wyoming was able to achieve through actions taken at the collective choice level in the second game or by interstate water banking and marketing transactions in the third game.

RECOMMENDATIONS

We recommend that the basin states and the federal government explore the possibility of replacing the 1922 compact with a federal interstate compact which:

- establishes an interstate compact commission, perhaps modeled after that now in place in the Delaware River Basin;
- provides that this commission be served by a technical staff, either within the present Bureau of Reclamation or apart from it, whose mission should be to conduct technical studies for the commission aimed at discovering common interest solutions to drought and other water management problems;
- establishes an advisory committee to the commission composed of representatives of all major water user groups, including agricultural, industrial, and municipal water consumers, hydroelectric power interests, environmental organizations, recreational users, and, last but certainly not least, Indian tribes;
- mandates consideration of meeting nonconsumptive water demands and uses on a no less urgent and important basis than that of serving consumptive uses;
- establishes long-term allocations of Colorado River water in proportion to current demands, rather than to 1922 allocations;
- provides for proportional sharing of short-term (drought) shortages, much as does the current upper basin compact;
- is empowered to encourage and facilitate interstate water banking and marketing; and
- is authorized to conduct joint explorations with Mexican entities of possibilities for restoring and maintaining the estuarine ecosystem of the Gulf of California (Sea of Cortez). Equitable cost sharing provisions should be an important part of such an innovation.

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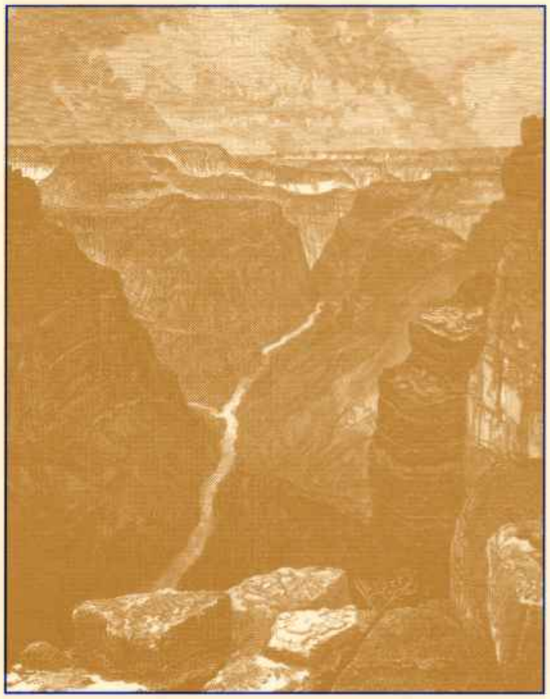

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John Wesley Powell, October 1884

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