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

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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

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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 inter-disciplinary 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 socio-demographic 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 precluded 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 non-marketed benefits. Monetary demand functions for recreational use of water were approximated for flat-water 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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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.

LITERATURE CITED

Booker, James F., 1995. Hydrologic and Economic Impacts of Drought Under Alternative Policy Responses. Water Resources Bulletin 31(5):889-906.

Booker, James F. and Bonnie G. Colby, 1995. Competing Water Uses in the Southwestern United States: Valuing Drought Damages. Water Resources Bulletin 31(5):877-888.

Burton, Ian, R. W. Kates and G. F. White, 1993. The Environment as Hazard (Second Edition) (First Edition, 1978). Guilford Press, New York, New York.

Clyde, E. W., 1986. Institutional Response to Prolonged Drought. *In:* New Courses for the Colorado River: Major Issues for the Nest Century, G. D. Weatherford and F. L. Brown (Editors). University of New Mexico Press, Albuquerque, New Mexico, pp. 109-138.

Easterling, W. E. and W. E. Riebsame, 1987. Assessing Drought Impacts and Adjustments in Agriculture and Water Resource Systems. *In:* Planning for Drought: Toward a Reduction in Societal Vulnerability, D. A. Wilhite and W. E. Easterling (Editors). Westview Press, Boulder, Colorado, pp. 11-27.

Englebert. E. A. and A. F. Scheuring (Editors), 1984. Water Scarcity: Impacts on Western Agriculture. University of California Press, Berkeley, California.

Fritts, H. C., 1984. Physical Limitations of Water Resources: Discussion. *In:* Water Scarcity: Impacts on Western Agriculture, E. A. Englebert and A. F. Scheuring, (Editors). Berkeley, University of California Press, Berkeley, California, pp. 44-48.

Gregg, F. and D. H. Getches (Principal Investigators), 1991. Severe, Sustained Drought in the Southwestern United States: Phase I Completion Report to the Man and the Biosphere Program, University of Arizona, School of Renewable Natural Resources, U.S. Dept. of State, Tucson, Arizona. National Technical Information Service Document No. PB92-115013.

Harding, Benjamin L., Taiye B. Sangoyomi, and Elizabeth A. Payton, 1995. Impacts of a Severe Sustained Drought on Colorado River Water Resources. Water Resources Bulletin 31(5):815-824.

Hardy, Thomas B., 1995. Assessing Environmental Effects of Severe Sustained Drought. Water Resources Bulletin 31(5):867-875.

Henderson, James L. and William B. Lord, 1995. A Gaming Evaluation of Colorado River Drought Management Institutional Options. Water Resources Bulletin 31(5):907-924.

Kenney, Douglas S., 1995. Institutional Options for the Colorado River. Water Resources Bulletin 31(5):837-850.

Kneese, A. V. and G. Bonem, 1986. Hypothetical Shocks to Water Allocation Institutions in the Colorado Basin. *In:* New Courses for the Colorado River: Major Issues for the Nest Century. G. D. Weatherford and F. L. Brown, (Editors). University of New Mexico Press, Albuquerque, New Mexico, pp. 87-108.

Krannich, Richard S., Sean P. Keenan, Michael S. Walker, and Donald L. Hardesty, 1995. Social Implications of Severe Sustained Drought: Case Studies in California and Colorado. Water Resources Bulletin 31(5):851-865.

Lord, William B., James F. Booker, David M. Getches, Benjamin L. Harding, Douglas S. Kenney, and Robert A. Young, 1995. Managing the Colorado River in a Severe Sustained Drought: An Evaluation of Institutional Options. Water Resources Bulletin 31(5):939-944.

Maass, A. *et al.*, 1962. Design of Water Resource Systems. Cambridge, Harvard University Press, Cambridge, Massachusetts.

MacDonnell, Lawrence J., David H. Getches, and William C. Hugenberg, Jr., 1995. The Law of the Colorado River: Coping With Severe Sustained Drought. Water Resources Bulletin 31(5):825-836.

Meko, David, Charles W. Stockton, and W. R. Boggess, 1995. The Tree-Ring Record of Severe Sustained Drought in the Southwest. Water Resources Bulletin 31(5):789-801.

Pearce, D. W. and R. K. Turner, 1990. Economics of Natural Resources and the Environment. Johns Hopkins University Press, Baltimore, Maryland.

Schmid, A. A., 1989. Benefit-Cost Analysis: A Political Economy Approach. Westview Press, Boulder, Colorado.

Tarboton, David G., 1995. Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States. Water Resources Bulletin 31(5):803-813.

Sangoyomi, Taiye B. and Benjamin L. Harding, 1995. Mitigating Impacts of a Severe Sustained Drought on Colorado River Water Resources. Water Resources Bulletin 31(5):925-938.

U.S. Water Resources Council, 1973. Procedures for Evaluation of Water and Related Land Resource Projects. Federal Register 38, 174, 24766-24869.

U.S. Water Resources Council, 1983. Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies. Washington, D.C.

Warrick, R. A., 1975. Drought Hazard in the United States: A Research Assessment. Monograph No. 4, Natural Hazards Research and Applications Information Center, University of Colorado, Boulder, Colorado.

White, G. F., 1984. Problems, Findings and Issues. *In:* Water Scarcity: Impacts on Western Agriculture, E. A. Englebert and A. F. Scheuring, (Editors). University of California Press, Berkeley, California, pp. 472-484.

Wilhite, D. A. and Michael Glantz, 1987. Understanding the Drought Phenomenon: The Role of Definitions. *In:* Planning for Drought: Toward a Reduction in Societal Vulnerability, D. A. Wilhite and W. E. Easterling (Editors). Westview Press, Boulder, Colorado, pp. 11-27.

Wilhite, D. A. (Editor), 1993. Drought Assessment, Management, and Planning: Theory and Case Studies. Kluwer Academic Publishers, Norwell, Massachusetts.

Young, R. A. (Editor), 1994. Coping with Severe Sustained Drought in the Southwestern United States. Draft Research Project Technical Completion Report, Utah Water Research Laboratory, Utah State University, Logan, Utah.