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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.

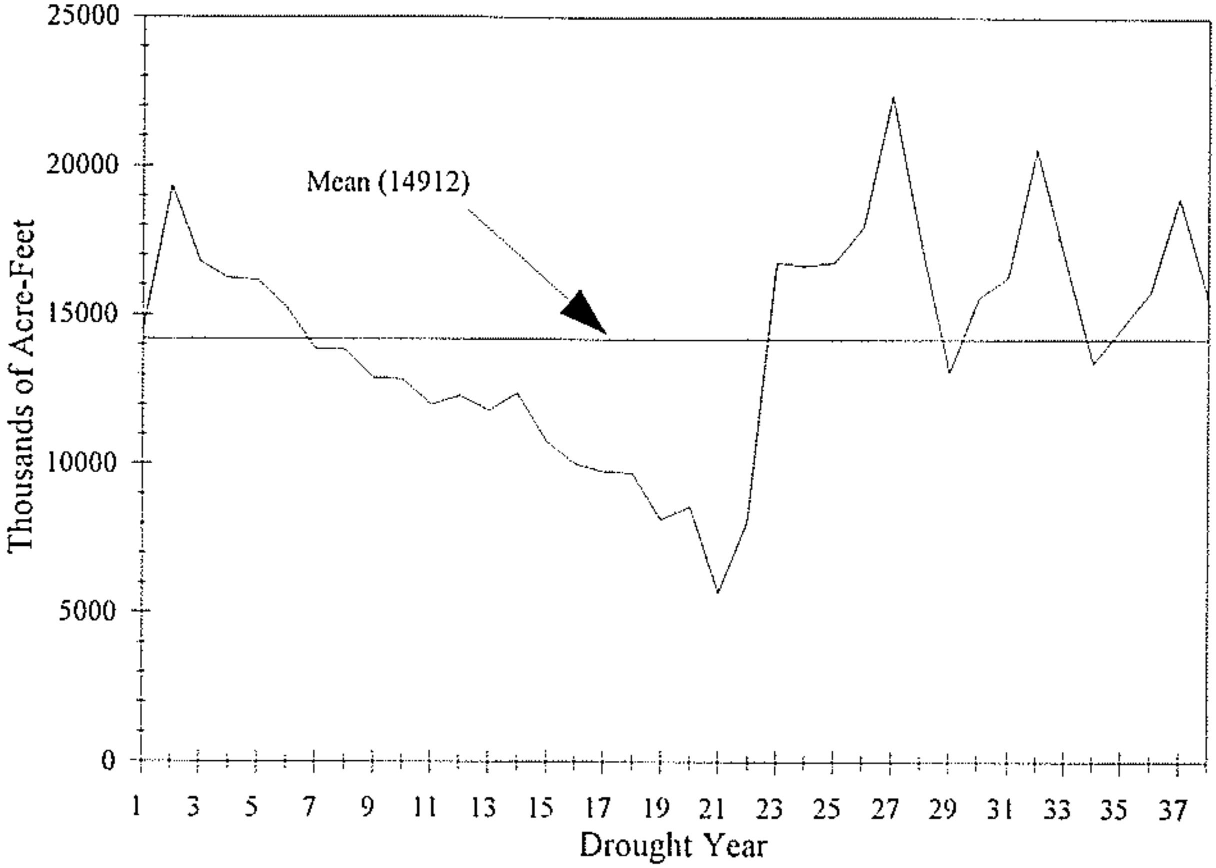

Figure 1. Severe Sustained Drought Scenario Utilized in the AZCOL Gaming Simulations (after Lord *et al.*, 1995).

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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