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FINAL REPORT

A STUDY OF THE WATER RESOURCES OF THE SAN PEDRO BASIN AND OPTIONS FOR EFFICIENT AND EQUITABLE WATER MANAGEMENT

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Submitted by the University of Arizona San Pedro Interdisciplinary Study Team
to the Upper San Pedro Basin Water Resources Council

Water Resources Research Center
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EXECUTIVE SUMMARY

The people of the Upper San Pedro River Basin are concerned about two possible water resource problems, among others (water quality problems and transboundary issues, although worthy of investigation, lie outside the scope of the present study). These concerns include:

1) accelerated pumping as a consequence of continued growth in the Sierra Vista area may deplete the groundwater reservoir upon which all depend, and thus jeopardize the long-run sustainability of the community;

2) water use throughout the upper portion of the basin may reduce stream flows in the San Pedro River and harm the San Pedro Riparian National Conservation Area, a natural and economic asset to the region.

In Spring of 1990, the Upper San Pedro Basin Water Resources Council requested that a student-faculty team from the University of Arizona examine the water resources situation of the basin, report to the Council concerning the nature of that situation and any problems that might require a local response, identify and evaluate possible response options, and provide a computer model capable of supporting further investigation and planning by local entities.

This document is the report of that university study team. The highlights of the report are contained in this summary. Further detail can be found in the main body of the report. The computer planning model, named WATERBUD, has been given to the Cochise County Flood Control District, which contracted with the University. A number of student reports were prepared (some are still being completed) as a part of the study, copies of which will be available in the library of the Cochise County Flood Control District.

The university team developed four models to help it analyze the water resources situation of the Upper San Pedro Basin. The first of those models is a detailed groundwater model of the southwestern sub-basin, an area which includes the city of Sierra Vista and Fort Huachuca. This model is an expansion and revision of the MODFLOW model of the U.S. Geological Survey (USGS), and later updated by the Arizona Department of Water Resources. That earlier version modelled only the groundwater, and was thus incapable of casting light upon the stream-aquifer interaction which must be understood in order to address protection of the riparian area.

The expanded MODFLOW model is not a fully integrated groundwater-surface water model, but it does address part of the stream flow issue, the contribution of groundwater to maintaining base flow. It covers one-fourth of the Upper San Pedro Basin (the Sierra Vista area), and addresses hydrologic aspects of the concerns listed above. This model is the most detailed and hydrologically sophisticated of the four models, and is the one best suited to address the question of sustainability in the Sierra Vista area. This model is the subject of a companion report.

Analyses using the revised MODFLOW model indicate that pumping from the deep regional, or basin fill, aquifer is creating an ever deepening and spreading cone of depression in the Sierra Vista area. However, this overpumping has less impact upon the flow in the San Pedro River than previously expected. The reason is that the regional aquifer is linked with the river only indirectly, through the shallow floodplain aquifer which follows the course of the river and which sustains virtually all of the irrigation pumping. This hydrologic relationship is a tenuous one, and transit times are very long. Pumping from the regional aquifer has therefore a modest impact upon streamflow, at least throughout the twenty year period of analysis which was used.

Our studies show a progressive decline in the contents of the regional aquifer, a decline which may be expected to accelerate with continued pumping. Although the large volume of water in the regional aquifer is capable of sustaining existing and future development for many years, a point in time will come, when the consequences of continued depletion must be faced. The earlier these consequences are faced and addressed, the more options will be available to stop or reverse this process.

The second model developed by the university team is a basin-wide model of the surface water-groundwater system, and of the institutional rules for allocating water within it. This model has a greater compass, geographically, hydrologically, and institutionally, than does MODFLOW and includes runoff volumes in its calculations. It is an implementation of the MODSIM network optimization model developed by John Labadie at Colorado State University. It is useful for addressing basin-wide hydrologic issues and also for investigating institutional options.

The analyses performed with MODSIM indicate that two factors explain most of the flow variance in the San Pedro River. They are surface runoff and irrigation pumping from the floodplain aquifer. Runoff replenishes the contents of the floodplain aquifer during wet periods. Continued pumping from the floodplain aquifer during dry periods depletes the contents of the floodplain aquifer and reduces its contribution to maintaining the base flow of the stream.

Irrigation pumping from the floodplain aquifer is largely and quickly offset by recharge from runoff, so that the net overdraft of the floodplain aquifer is much smaller than that of the regional aquifer. However, the stream is intimately linked with the floodplain aquifer, and, next to drought, irrigation pumping has the greatest effect upon stream flow. Increased irrigation pumping beyond present levels will result in depletion of the floodplain aquifer and consequent reductions in stream flows.

The third model, called WATERBUD, was developed by the university team and is a spreadsheet representation of the hydrology, economics, and water resource allocation institutions of the basin. Its compass is broader than that of the MODSIM model, although it lacks that model's useful optimization capability. It is a true planning model, in the sense that it permits the specification of various policy options and the exploration of their hydrologic and economic impacts under various scenarios of climate, population, and economic change in the

future. Information about hydrologic conditions from MODFLOW and MODSIM was used in this model and it has been tested for consistency with them.

Several policy options have been identified by the university team. The **first option** is to proceed without changing the existing water management institutions. The **second option** is to create an urban Active Management Area (AMA) under the 1980 Groundwater Management Act similar to those created for Phoenix, Prescott, and Tucson. The **third option** is to create a "customized" Active Management Area which preserves the "safe yield" goal and safeguards instream flows, but relies upon a pump tax rather than regulation to control water use. The **fourth option** emphasizes water supply augmentation rather than demand management to achieve safe-yield. The **fifth option** is pure demand management, primarily conservation measures, to illustrate the contrast between this approach and the water supply augmentation option. These policy options have been developed to demonstrate a general range of choice and the kinds of consequences each may produce. In other words, they are intended to inform the planning and decision-making process, but not to substitute for the creative process of developing responsive, effective, and politically acceptable options within the basin.

Each water management option should be evaluated according to its ability to achieve its goals under a variety of possible future conditions. Accordingly, the university team has defined a number of possible future scenarios. These scenarios are characterized by different assumptions about: 1) the **future climate** (average or dry); 2) **population growth** (medium or high); and 3) **economic activity** (with or without agricultural expansion).

The hydrologic system of the San Pedro Basin responds differently to the serval policy options, depending upon which scenario is chosen. Changes in climate have the greatest effect upon stream flow. However, changes in population most influences the rate of depletion of the regional aquifer and changes in agricultural development accounts for the greatest change in water levels in the floodplain alluvium.

WATERBUD analyses indicate that short-term stabilization of water levels in the floodplain aquifer requires policy intervention only in the agricultural development scenarios, and can be achieved by any option which restricts agricultural pumping in the southern half of the Upper San Pedro basin. These include both the conventional and "customized" AMAs. No option tested can protect instream flows in the riparian area during times of drought and high agricultural pumping, without additional management tools, such as the pumping of the regional aquifer to enhance flows.

The fourth model employed by the university team is a plan evaluation model, MATS, developed by the Bureau of Reclamation. This model attempts to represent the values of the people of the basin, not its hydrology or institutions. Analysis of interviews with basin residents suggest that three different, relatively homogeneous, groups can be identified. The **first group (I)** emphasizes economic factors in comparing the desirability of different water management outcomes. They oppose any policies which would increase tax burdens, whether to protect the environment or to facilitate population growth. The **second group (II)** emphasizes environmental

factors, particularly the status of the riparian area. They oppose future population growth, and are less concerned about economic factors. The **third group (III)** is especially concerned with preserving local control over water management decisions. They support protection of the riparian area and favor a modest level of population growth.

The MATS model produced weighted preferences of each of the three groups. These preferences can be used to evaluate any policy option, as it would perform under any set of assumed future climate, economic, and demographic conditions. The three identified groups would not agree on which of the five policy options is best. Furthermore, each would prefer the status quo to most of the five options. There is clearly no local mandate for institutional change, if the possible changes are limited to those explored in this study.

An important caveat to the findings of the MODFLOW, MODSIM, WATERBUD, and MATS models is that all of the policies and their projected impacts are based upon a twenty-year period of analysis, during which time the long-term implications of increasing pumping from the regional aquifer have yet to emerge strongly. Such pumping will have its greatest effect on the cost and availability of water to residents of the Sierra Vista area, but it will also affect stream flow in the San Pedro River, although it takes more than twenty years for those effects to be strongly felt.

Future analyses should include a longer period of analysis, should investigate drought coping policy options (such as dry year leasing of irrigation water), and should be directed at the analysis of policy options which incorporate many of the elements of the "customized" AMA. Members of the San Pedro Water Resources Management Council should view these results as indicative of the kinds of policy explorations which they now have the analytical capability to pursue over the coming months. The emphasis now should be upon generating new and improved policy options capable of addressing regional water problems which are now better understood than they were before.

A STUDY OF THE WATER RESOURCES IN THE UPPER SAN PEDRO BASIN AND OPTIONS FOR EFFICIENT AND EQUITABLE WATER MANAGEMENT

Introduction

This report was prepared by graduate students and faculty at the University of Arizona based on work performed over the course of a year long workshop and applied research project. The Cochise County Flood Control District and the University of Arizona provided support for this project, which was guided by the San Pedro Water Management Council and its technical committee. The objectives of this project were to assist the Council in identifying water management objectives and policy options capable of meeting these objectives and to provide analytical aids to the Council for their task of setting objectives and evaluating available policy options.

An Interim Report (Interim Report, Upper San Pedro Water Resources Planning Report, January, 1991) addressed in detail the identification of water management objectives and policy options. The main topic of this Final Report are the analytical tools developed to assist the Council in making water management decisions for the basin. Four separate models were developed to simulate the effects of various hypothetical conditions on important decision variables; each model produces results useful at a different level of analysis regarding different kinds of questions about how the variables interact.

Following is a brief description of the San Pedro basin, its physical characteristics, water use history, and social setting, the models are described. A separate chapter is devoted to each model, beginning with the hydrologic model, the two management models, and ending with the model that evaluates policy options in terms of major social values. A summary chapter integrates the significant results of sample runs of the models and indicates how the models are used together as decision tools. Supporting materials for the models can be found in the appendices, and the individual student papers upon which this report is based are in the library of the Cochise County Flood Control District.

Description of the Upper San Pedro River Basin

The Upper San Pedro River Basin occupies about 1800 square miles in southeastern Arizona and about 700 square miles in northern Sonora, Mexico (Putnam, et. al., 1987). The geological characteristics of southeastern Arizona's Upper San Pedro River basin are typical of those found in the Basin and Range Physiographic Province, an area of elongated mountain chains separated by alluvium filled basin, in which it is situated. The basin trends in a north-south direction and is bounded on the west by the Huachuca, Mustang, Whetstone, and Rincon

Mountains, and on the east by the Mule, Dragoon, Little Dragoon and Winchester Moutains. The basin has been partially filled with sediments eroded off of the surrounding mountains, and slopes downward from south to north.

The basin is separated into upper and lower divisions near its midpoint, at the spot known as "The Narrows", an area of bedrock constriction in the valley 12 miles north of Benson, Arizona, (Figure 1). The upper basin, composed of the Benson and Sierra Vista subwatersheds, lies to the south extending into Mexico, while the lower basin, composed of the Aravaipa, Winkleman, and Redington sub-basins, continues on to the north. The valley-floor elevation in the upper basin ranges from about 3,500 feet where the San Pedro River exits the basin at "The Narrows" to 9,466 feet at Miller Peak in the Huachuca Mountains (Roeske and Werrell, 1973).

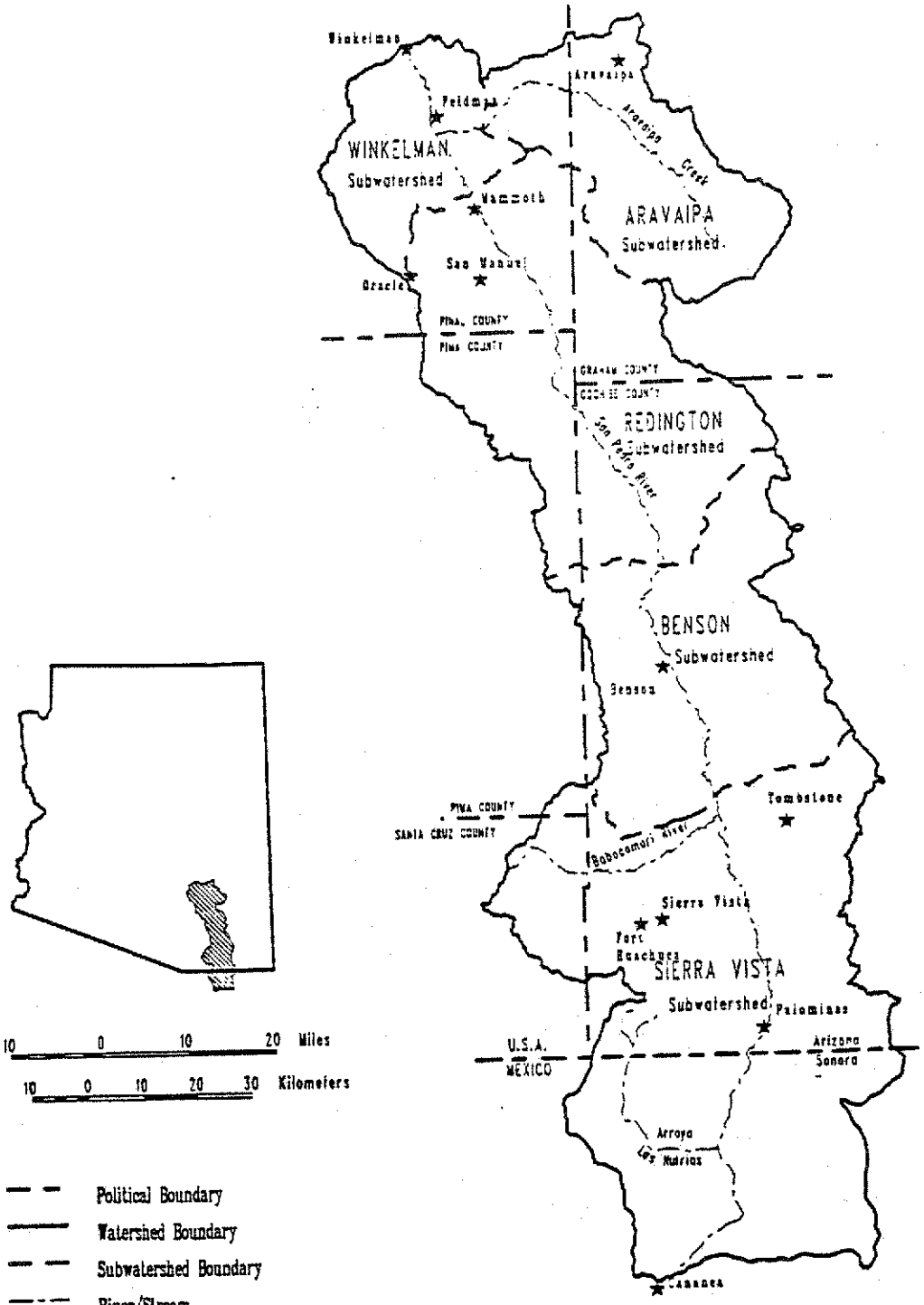
Climate in the area is semi-arid, with warm summers and moderate winters. The higher elevations are more humid, cooler, and receive more precipitation. Precipitation is extremely variable on both a monthly and a yearly basis. Annual average precipitation ranges from 10 to 12 inches along the San Pedro River and increase with elevation to more than 30 inches in the Huachuca Mountains (ADWR, 1990). The distribution of the precipitation is bimodal, with about 50-60% of the annual total occurring in the summer "monsoon" season and 20% occurring in the winter months (USDI, 1987). Spring and fall are usually very dry.

The San Pedro River flows from south to north, having its headwaters approximately 25 miles south of the international border. Most of the tributaries carry water only after heavy precipitation, and even the San Pedro River is intermittent over part of its length. The San Pedro River is perennial for 36 of its 62 river miles in the Upper San Pedro Basin (ADWR, 1990). The remainder of the River is intermittent. The perennial reach of the river exists from near Hereford to the diversion dam operated by the St. David Irrigation District (SDID) about 5 miles south of St. David.

The perennial flow is due to the discharge of groundwater from the floodplain aquifer. Some of the perennial flow is due to groundwater from the regional aquifer being forced upward by shallow bedrock (ADWR, 1990). Most of the perennial reach is within the boundaries of the San Pedro Riparian National Conservation Area (SPRNCA), which is managed by the Bureau of Land Management.

While surface water resources in the basin are fairly limited, vast quantities of water exist below the ground surface. The valley fill sediments, which are up to 1500 feet deep in some places (ADWR, 1990), contain most of this water. These valley fill sediments comprise a large "regional" aquifer which underlies most of the basin. In the upper basin alone it is estimated to contain up to 48 million acre-feet (maf) of water (ADWR, 1990). Water is recharged to the regional aquifer from along the mountain fronts and from stream channel infiltration. Groundwater travels towards the San Pedro River. ADWR (1990) estimates mountain front recharge to be 25,620 acre-feet per year (af/yr).

Figure One: San Pedro River Watershed



Source: Arizona Department of Water Resources 1990

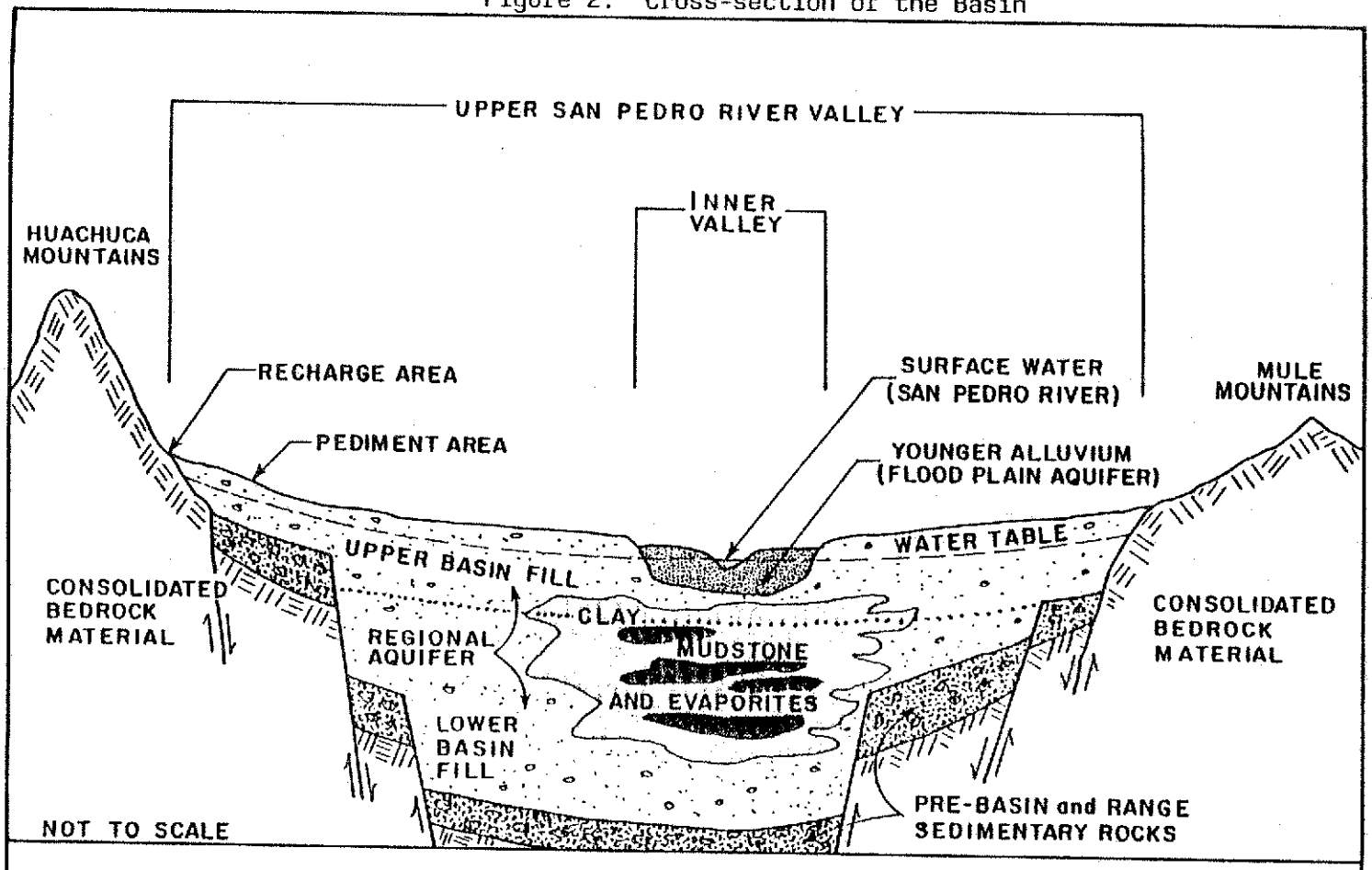
Additional water exists in the younger, shallower sediment deposited on top of the valley fill sediments by the San Pedro River and its tributaries. These "floodplain" aquifers are much smaller and narrower than the regional aquifer, ranging from 200 yards to several miles wide, and from only 40 to 150 feet deep (Putnam, et. al., 1987). By far the most significant of these floodplain aquifers is the one which lies beneath and along either side of the main stem of the San Pedro River. It is estimated that the floodplain aquifers in the upper basin contain a total of 0.5 maf of water (ADWR, 1990).

The floodplain aquifer acts as a conduit for the interaction between the groundwater and surface water systems (Figure 2). The floodplain aquifer is recharged by stream flow, upwater leakage and lateral flows from the regional aquifer, and deep percolation (return flows) from agricultural activities (ADWR, 1990). Groundwater flow in the floodplain aquifer is in the same direction as the gradient of the river. The water table in the floodplain aquifer exhibits seasonal fluctuations. However, there have been no net long term declines in water levels because groundwater withdrawn from the aquifer is replace rapidly during infiltration of San Pedro stream flow during periods of runoff.

Water can move back and forth between the regional and floodplain aquifers, though it usually moves from the regional aquifer towards the central floodplain aquifer because of prevailing pressure differences and gradients. Water also moves back and forth between the floodplain aquifers and the river; in some stretches the river is fed by groundwater "baseflows," while in other stretches water infiltrates from the river to the floodplain aquifer. Water flows perennially in reaches where it is fed by baseflows, and intermittently in the other reaches.

Relative to the surface runoff, water flows quite slowly in the underground aquifers. Though the rates are quite variable depending on the exact location, it has been estimated that the average flow rate in the regional aquifer is 22.6 feet per year (Putnam, et. al., 1987). This means that changes made to the flows of the regional aquifer (such as from groundwater pumping) take a substantial amount of time to be propaged to downstream areas, though they might eventually be observed depending upon the downstream distance and the significance of groundwater basins of the basin between. Water flows at much faster rates in the floodplain aquifers because they are much more permeable than the regional aquifer. This means that changes to the flow rates are much more quickly reflected in stream flow levels and, therefore, at other locations in the floodplain aquifers due to the interconnection of the stream flow and the floodplain aquifer.

Figure 2: Cross-section of the Basin



Source: Arizona Department of Water Resources, 1990

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Human Development and Use

The first permanent Anglo settlement in the basin was established in 1877, when both Fort Huachuca and the town of St. David were founded. The Mormons at St. David were the first Anglos to establish an extensive irrigation system, using water from the San Pedro River as the Indians before them had done. In 1878 the mining industry became established in the basin as the Tombstone mine was founded and a smelter was built near Bisbee. The 1880s saw rapid development of mining and farming in the basin, as well as the development of ranching and railroads.

Several cities associated with these industries were founded and grew during this time. The town of Tombstone boomed around the mine, and was Arizona's largest city in the 1880s. The Hereford area developed around the smelter, ranching, and railroad station in the southern end of the basin. The town of Fry (renamed Sierra Vista in 1956) developed outside the main gate of Fort Huachuca, and the St. David, Pomerene, and Benson communities developed around irrigated agriculture and the railroad station at Benson.

Large scale mining activities in the upper San Pedro basin continued until 1975 in the Bisbee area, with some mining still ongoing in both the Bisbee and Tombstone area. Agriculture expanded steadily through the 1970's, with some decline to the current level in the 1980's. Urban areas have continued to expand. Sierra Vista is the largest town in the area, as urban growth concentrated around Fort Huachuca. Manufacturing, services, and public administration joined agriculture and national defense as the primary employers in the basin's economy. In recent years, many people, including retirees and tourists have been attracted to the basin because of its climate, location, history, and general aesthetic values.

With growth in the basin has come general increased water use for both agriculture and domestic uses. Early surface water irrigation was augmented by the development of methods to use the basin's groundwater resources, which quickly became the major source of water in the basin. In 1892 the first artesian well was drilled in the northern end of the basin, and by 1903 there were over 200 wells between Benson and Fairbanks. The amount of land irrigated by groundwater increased especially rapidly after around 1930. Most of the wells currently supplying water in the basin were drilled in the last 40 - 50 years, with an increase in agricultural wells after 1930 and an expansion in domestic wells beginning in the 1950s.

Virtually all of the urban and industrial wells draw water from the deeper regional aquifer. Most of the irrigation wells are now located in the permeable floodplain aquifer alongside the San Pedro River, with some agricultural pumping from the regional aquifer. Agriculture is currently the major user of water in the upper San Pedro basin, accounting for approximately 70% of all cultural depletions. Municipal and domestic uses account for most of the remaining water withdrawals (approximately 22%) in the basin. Water uses in the Upper San Pedro basin are summarized in the following table:

Table 1
Upper San Pedro River Basin Water Usage:
1989-1990 Development Conditions (Acre-feet per year)

Cultural depletions	Sierra Vista	Benson
Irrigation	13,540	16,840
Domestic	450	250
Municipal	7,918	885
Stockponds	1,750	910
Resevoirs	150	310
Mining	2	0
Industrial	50	380
Total Cultural	23,860	19,575
Natural Depletions		
Channel Evaporation	910	670
Phreatophytes	14,510	18,600
Total Natural	15,420	19,270
Total Use	39,280	38,845

Source: Arizona Department of Water Resources, 1990.

Management Opportunities

The Upper San Pedro Basin Water Resources Council was created to advise the Cochise County Board of Supervisors in developing a water resources management plan for the basin. Although, some knowledge about the hydrology of the basin was available, more information was needed. Uncertainty surrounded questions such as the influence of pumping from the regional aquifer upon stream flows in the river and its tributaries. Other questions included:

1) How could the desires of the community be translated in water management objectives?

2) How would achievement of a particular water management objective affect the lives of basin residents?

3) What management options exist?

4) Which options would be most effective in achieving desired objectives?

Several water management issues have emerged in the basin. **First**, urban growth and the associated pumping of numerous wells have led to the growth of a localized, regional cone of depression in the Sierra Vista area. Putnam, et. al. (1987) estimated the average decline to be about 1.4 acre-feet per year. ADWR (1990) reported that the cone of depression was

approximately 7.5 square miles in extent in 1986. This development has raised local concerns of possible groundwater table declines in that area, causing in the future, greater pump lifts, a possible decline in water quality, and possible subsidence, and eventually, a possible reduction in stream flow.

Second, the establishment of the San Pedro Riparian National Conservation Area in 1988 has focused attention on the need to protect stream flows and riparian habitat in the basin, which may be threatened by groundwater depletion. This area encompasses 47,688 acres of land stretching approximately 36 miles long and 2.6 miles wide. Concerns about future water management efforts for the area include whether there will be enough water in the future to maintain this unique riparian habitat and the important natural and recreational amenities it provides, and other riparian areas in the basin along the San Pedro, the Babocomari, and other important watercourses.

Linked Models Approach

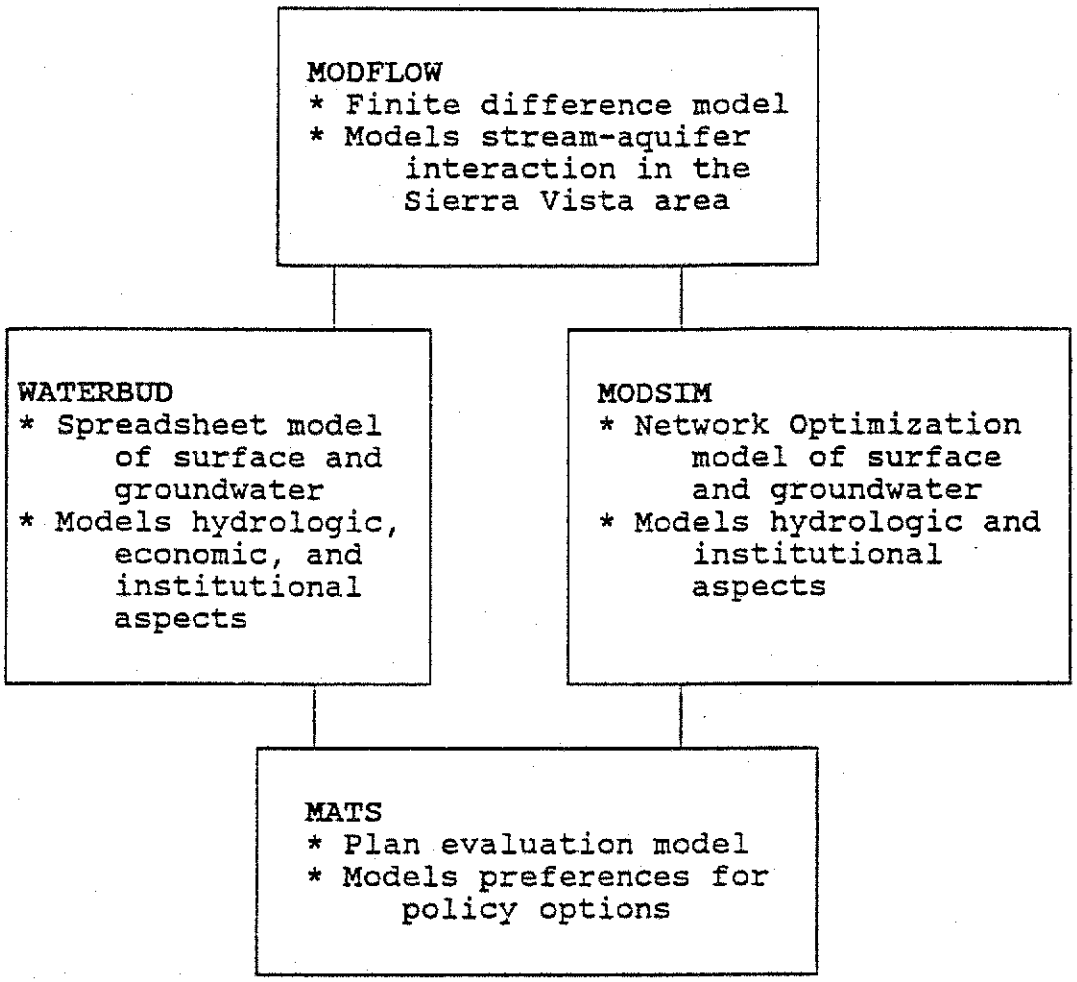
To address these water management concerns and questions, the university team employed a linked model approach. Most water management planning efforts require an interdisciplinary approach in which hydrologic, environmental, economic, legal, and political aspects can be addressed. Linked models are commonly used in hydrology, where surface and groundwater models are sometimes linked, and in economics, where programming and demand models are sometimes linked.

In water resources planning, the linked model approach is especially useful for evaluating different options for the management of water resources, a central focus of this study. Evaluation of the available policy options requires two quite different kinds of information. The first is projection of the consequences of each option, if implemented. The second is an evaluation of those consequences for those who will be affected by them.

The San Pedro Basin contains within it many different groups and interests who are stakeholders in how the basin's water resources are managed. Policy options will differ in their impacts upon these diverse interests, and each group will weigh those impacts differently as it strives to formulate its own preferences among the options.

The first type of information - the projection of the consequences of each water management options - was generated through the use of the MODSIM and the WATERBUD models. For the second type of information - the evaluation of the consequences of each water management option on the different groups and interests in the basin - another model - MATS was used. Each of these models is described in detail in the following sections of this report. The following diagram (Figure 3) illustrates the relationship between these models and their individual attributes.

Figure 3
Linked Model Approach



Values and Objectives

The identification of pertinent social goals and objectives is a necessary step in water resources planning for water management options developed without properly addressing them have little chance of acceptance or implementation. Management decisions affect people as well as resources. The goals and objectives for the management of water necessarily must go beyond questions of technical feasibility to include social, economic and political considerations. This identification of relevant water management objectives and goals for the Upper San Pedro Basin was also a focus of this study.

The residents of the San Pedro River Basin share many important water related values. For example, many value the natural amenities available in the area, especially those provided by stream flow in the San Pedro River and other basin streams. Many also value the rural nature of much of the basin and believe it enhances the lives of city dwellers as well as those who live in the countryside. In addition, most are concerned with the economic viability of the basin communities and rural residents.

The San Pedro Basin, like other communities, is not homogeneous with respect to the values held by its members. This situation makes decision-making for the entire community more difficult. Conflict is inevitable in community decision-making, as values and interests clash. The planning process makes those conflicts explicit, and provides the information which is needed to resolve them successfully. Policy options which will be acceptable to major stakeholders can be devised when conflicts are recognized, and, their roots are understood. Otherwise, they can persist indefinitely.

One initial task of the university team was to establish the planning objectives to guide the search for policy options. A review of existing reports and other documents of the San Pedro Water Management Council and the San Pedro Water Resources Association revealed the following water resource management objectives had previously been discussed:

1) Maintain sufficient flow in the San Pedro River to preserve and protect the riparian environment and promote public enjoyment of those areas;

2) Ensure adequate groundwater supplies to support future growth and population expansion;

3) Prevent water transfers out of the basin;

4) Establish a single entity to manage the basin's water resources;

5) Educate and otherwise induce the population to adopt wise water use behaviors;

6) Maintain and enhance water-dependant activities within the basin.

Some, but not all, of those listed are above are appropritely termed "objectives", but each required further definition for the purposes of this study. One exception is the establishment of a single management entity for the basin. This is clearly not an objective but a means to attaining other objectives; it helps achieve the attainment of what are properly called "objectives". Prohibitions on transfers and encouragement of water-saving behaviors also seem to be more in the nature of means than of objectives.

For this study, the University team suggested the following planning objectives:

1) To maintain and enhance the water-dependent riparian ecosystem of the San Pedro Riparian National Conservation Area;

2) To satisfy the reasonable water demands of current residents of the basin, with reasonability interpreted to mean both no radical lifestyle changes (such as the elimination of landscape irrigation) and the imposition of additional water costs on such residents only to the extent justified by the costs of serving them, as opposed to new development;

3) To support new development and growth within the basin;

4) To maintain a water-dependent irrigated agricultural sector for so long as the substantial water requirements of that sector neither foreclose additional urban growth nor threaten critical riparian values.

It should be noted also that some of these objectives may be competitive, or mutually inconsistent. It seems almost certain, for example, that at some level of water use in the Sierra Vista area, the objectives of maintaining riparian habitats and of encouraging municipal growth will become competitive, if they are not already. Ideally, policy options should be found which could postpone the time at which difficult tradeoffs between these two objectives must be considered and made. However, it must also be acknowledged that such options may not be available, or may only succeed in delaying the need for difficult choices.

Scenarios

Water supply conditions in the upper San Pedro basin are influenced by a variety of environmental conditions, which unlike policy options, are beyond the control of basin residents. The university team identified three changes in the environment which are most likely to affect the water resources status of the basin: 1) **population growth**; 2) **variations in climate**; and 3) **regional or national economic conditions** affecting the economic feasibility of irrigated agriculture.

The study team established a range over which each change could vary with each of the three changes assigned a high value and a low value. The low value represents conditions that

have the smallest impact on the water supply system and the high value represents conditions that have the greatest impact on the water supply system. These values represent the full range of impacts expected from each of the three changes on the water supply of the basin.

For example, for population growth, the low range value is set to approximate recent historical growth rates for each area of the basin and the high range value is set to represent more rapid, yet still plausible growth rates of an additional 2% per year. Also, population growth because of the Fort Huachuca was also accounted for by assigning a single increase of 3,000 personnel and another 4500 for their dependants.

The low range value for climate was set to represent average hydrologic conditions. These average conditions were based on average precipitation and runoff and stream flow data obtained from ADWR. The high range value was set to represent drought conditions in the basin. Precipitation and USGS stream gaging records were used to determine two types of drought conditions: 1) for the WATERBUD model, drought was set at "severe" case year based on historical records which was assumed constant over the twenty year period; 2) for the MODSIM model, a 10 year data set representing a drier than normal period from 1967 to 1976 was selected (partly because these are the only years when the Benson and Tombstone gages were in operation along with the Charleston and Palominas gages). For this period, the mean annual flow at Palominas was 27.5% below normal and tributary runoff, 21.1% below normal.

The low range value for agricultural development was set at a 0% annual growth rate in irrigated agriculture, and the high range value was set at 3.5% growth, the rate of agricultural growth in the 1970s.

The values for the three changes were then grouped together in various combinations to represent possible future conditions. Five different scenarios were chosen as representative and illustrative of the kinds of impacts which might be experienced in the basin. **Scenario A** has the least impact on the basin's water supply, while **Scenario B** has the greatest. The remaining three scenarios are each intended to highlight the impact of a particular change, i.e., **Scenario C** shows the impact of population growth, **Scenario D** shows the impact of drought, and **Scenario E**, the impact of growth in irrigated agriculture.

Scenario A. This scenario is designed to show all three external changes in their "low" values, so that conditions having the lowest impact on the water resources of the basin prevail. Population growth is moderate, climate follows historical patterns, and irrigated agriculture is using water at 1989-90 levels of use. This scenario represents the "average case" for water supply conditions.

Scenario B. This scenario is designed to show all three external changes in their "high" values, so that conditions having the greatest negative impact on the water resources of the basin prevail. Population growth is high, long term drought conditions exist, and irrigated agriculture is allowed to grow at the maximum rate of 3.5% annually because of favorable economic conditions. This scenario represents the "worst case" for water supply conditions.

Scenario C. This scenario is designed to highlight the impact of population growth on the water supply conditions of the basin. The low range values were used for both climate (historical) and agriculture (minimum water use) but the high value used for population growth.

Scenario D. This scenario is designed to highlight the impact of changes in climatic trends, namely drought, on the water supply conditions of the basin. Under this scenario, the low range values were used for population (moderate growth) and agriculture (minimum water use), but climate variables are set to represent long term drought.

Scenario E. This scenario highlights the impact of agricultural water use on the water supplies of the basin. The low range values were used for population (moderate growth) and climate (historical), while regional or national economic conditions favor the maximum rate of growth in agricultural use of water.

These scenarios are summarized in the following table:

Table 2: Management Scenarios

	Future Conditions		
Scenarios	Population Growth Rate	Hydrologic Conditions	Irrigated Agriculture
A - Average Conditions	Current	Average	No growth
B - Worst Case	High	Dry	Growth
C - High Growth	High	Average	No growth
D - Drought	Current	Dry	No growth
E - Agricultural Expansion	Current	Average	Growth

Policy Options

A wide range of public policies could conceivably be used in the management of the water resources of the upper San Pedro basin. Five alternatives which illustrate the range of impacts that public policies may have on the water resources of the basin were chosen for this study. It is not anticipated that any of these policies will be adopted "as is;" rather, they are intended to show the range and nature of impacts on the water resources of the basin which can be affected through the use of public policies. Several other policy options were also

investigated by members of the University's research group and these are reported in the student papers which are located in the Cochise County Flood Control District Library.

The probable impacts of each of the five policy alternatives were estimated by the WATERBUD and MODSIM models under each of the five different scenarios, resulting in 25 different runs of each of the models for a total of 50 runs. However, not all of these runs were useful. Therefore the results are selectively summarized in a manner which highlights the impacts of the chosen scenarios and policy options. The results generated from these scenarios and alternatives will be useful in reaching informed judgments about the water management needs of the basin.

Following are the primary policy alternatives which were selected under these scenarios. Policy alternatives Two and Three each have several variants, for a total of ten alternatives.

Policy 1: Status Quo. Under this policy option, it is assumed that no changes are made in the current methods of managing the water resources of the basin. No laws are changed, no new agencies are created, no new regulations are promulgated. Water use patterns continue as they have historically, based on individual water use choices. This policy option is designed to represent "baseline" conditions which are expected to prevail under each of the five scenarios described above. As such, the results of using this policy alternative provide a useful reference point for the evaluation of the other potential policy alternatives.

Policy 2: Conventional Active Management Area. This policy option is designed to represent conditions which would exist if the upper San Pedro basin became an AMA with the same "safe yield" goal that exists in the Tucson, Phoenix, and Prescott AMAs. In this case, as with the Arizona Groundwater Management Act, "safe yield" is defined as the situation in which annual water consumption is equal to annual recharge (need to define). Under this option, **1)** municipal water uses are subject to gallons-per-capital-per-day (gpcd) restrictions; and **2)** agriculture is required to increase water use efficiency, and some irrigated acreage is retired (through purchase) in an attempt to reach safe yield.

Gpcd restrictions and irrigation efficiency requirements are tightened until safe yield is reached to see how severe these restrictions would have to be to meet this goal. In the extreme, if necessary, all irrigated acreage would have to be retired. Withdrawal fees, which may not exceed $5.00 per acre-foot, are used to help fund administration and enforcement, conservation, augmentation, and the retirement of some irrigated lands. This policy option can be used to show the types and severity of impacts of policy options that have safe yield as a goal.

There are three variants of Policy 2:

Policy 2-1 covers the effects of imposing a 150 gpcd limit on domestic consumption and requiring a minimum efficiency of 85% for all irrigation.

Policy 2-2 covers the same effects as Policy 2-1, except that 50% of all irrigated land is retired. Riparian vegetation is allowed to reclaim the retired lands only as hydrological conditions permit (what does this mean).

Policy 2-3 covers the same conditions as Policy 2-2, except that 100% of all irrigated land is retired; again, riparian vegetation is allowed to reclaim the retired lands only as hydrological conditions permit.

Policy 3: Customized AMA. The Arizona Groundwater Management Act does not specify mandatory goals or a single type of plan for all AMAs; rather, it provides a significant amount of flexibility in both cases. This policy was developed to show an alternative management approach - a market-based possibility - to the regulatory approach used in the conventional AMAs.

This AMA also assumes also a water management goal of safe yield but the method used in Policy 3 is quite different from that described in Policy 2. For this option, municipal conservation and irrigated acreage retirement is achieved through price controls, in the form of a "pump tax" on groundwater withdrawals. The pump tax is to be set sufficiently high to significantly restrict municipal water use and generate enough revenues to enable to buy out all irrigated agricultural lands, if necessary.

This option has two purposes: **1)** to determine how high such a tax would have to be to meet the safe yield and minimal stream flow goals; and **2)** to provide a way to evaluate impacts of collecting revenues for <u>any</u> management authority through taxes. With this policy option, it should be possible to see how high a tax would have to be, and where and on whom it would have to be placed, in order to achieve a specified level of revenues.

Policy 3-1 shows the effects of adding a $1.00 charge to customers for each 1000 gallons of water delivered by regulated water delivery services or pumped from irrigation wells ($325 for each acre-foot).

Policy 3-2 shows the effects of adding $2.00 per 1000 gallons ($650 per acre-foot).

Policy 3-5 shows the effects of adding $5.00 per 1000 gallons ($1625 per acre-foot).

Policy 3-10 shows the effects of adding $10.00 per 1000 gallons ($3250 per acre-foot).

The Arizona Groundwater Management Act would not permit a withdrawal fee in excess of $5.00 per acre-foot unless amended. Irrigator opposition to such an amendment would be strong. It is likely that a withdrawal fee of this magnitude or higher would virtually eliminate irrigation pumping (although we have not performed the economic analysis which would be needed to confirm this) while imposing only an annoying burden on domestic water users.

Policy 4: Water Supply Enhancement. This policy option consists of maximum attempts to increase basin water supplies, without any corresponding attempts to reduce water demand. The goal is to determine the extent to which these and similar measures can enhance the water resources supply of the basin.

Practicable measures to enhance water supplies in the basin are difficult to find. For this option, two measures were considered: 1) recharge of treated effluent and 2) cloud seeding efforts to increase precipitation. For the recharge of effluent, a 100% rate of recharge of all treated effluent to the regional aquifer is assumed. To estimate the total amount of effluent, it was assumed that municipal and domestic users return 50% of all water used and that 15% was assumed lost because of evaporation during treatment. Cloud seeding was modeled by assuming an increase in precipitation and a subsequent 10% in annual mountain front recharge. Importation of water from outside the basin was not included because of a lack of any economically feasible water sources.

Policy 5. Demand Management. This policy option consists of maximum efforts to reduce water demands without any corresponding attempts to increase water supplies. When compared to Policy 4 results, this should show how the two different approaches - demand vs. supply management - will impact the water resources situation in the basin.

The key features of this alternative are municipal and domestic conservation and improved agricultural efficiencies. A 25% reduction in municipal and domestic demand was assumed to be achieved through measures such as xeriscaping (the replacement of high-demand outdoor plants with lower water-demand ones) and low-flow indoor plumbing fixtures. Irrigation efficiencies were set at 85% and assumed to be achieved through land leveling and improvements in irrigation system efficiencies, although the cost of implementing such practices in the basin might be prohibitive under current economic conditions.

The policy options are summarized in Table 3:

Table 3: Management Options

POLICY OPTION	DESCRIPTION
Policy 1 - Status Quo	* No changes in water management, including laws and institutions * Historic water use patterns prevail * Represents baseline condition
Policy 2-1 - Conventional AMA	* Establishes an AMA with a goal of safe-yield * Municipal use subject to 150 gpcd limit * Irrigation efficiency set at 85%
Policy 2-2 - Conventional AMA	* Same as 2-1, except 50% of agricultural land retired
Policy 2-3 - Conventional AMA	* Same as 2-1 and 2-2 except 100% of agricultural land retired
Policy 3-1 - Customized AMA	* establishes an AMA with dual goal of safe-yield and minimum streamflows * pump tax of $1.00 per each 1000 gallons ($325 per acre-foot) * determine means for evaluating impacts of pump tax on water management goals * Riparian vegetation allowed to reclaim retired ag land
Policy 3-2 - Customized AMA	* same as 3-1 except pump tax $2.00 per each 1000 gallons ($650 per acre-foot)
Policy 3-5 - Customized AMA	* same as 3-1 and 3-2 except tax is $5.00 per each 1000 gallons ($1625 per acre-foot)
Policy 3-10 - Customized AMA	* same as 3-1 and 3-2 except pump tax is $5.00 per each 1000 gallons ($3250 per acre-foot)
Policy 4: Supply Enhancement	* Maximum attempts to increase basin water supplies * No reduction in demand * Includes treated effluent and precipitation enhancement
Policy 5: Demand Management	* Maximum attempts to reduce water demands * No increase in supply * Includes reduction in municipal due to conservation and increased irrigation efficiencies.

MODFLOW

Introduction

This model is a modified version of the model originally designed by Freethey (1982) and later updated by the Arizona Department of Water Resources. The computational model used for the study is MODFLOW, a Modular Three Dimensional Finite Difference Ground-water Flow Model developed by the U.S.Geological Survey.

MODFLOW has a modular structure that allows the user to incorporate a series of packages or modules to simulate different processes such as recharge, drains, evapotranspiration, river-aquifer interaction and pumping. A new integrated river-aquifer interaction program developed by Prudic (1989), which replaces the old river module previously used with MODFLOW, is incorporated in the model. The new stream routing program improves the representation of the stream-aquifer interaction of Southwestern rivers like the San Pedro. With the new program, portions of the stream are permitted to go dry and then flow again, and stream stage calculations are provided.

The model area covers the southwest section of the Upper San Pedro Basin. The area extends from 2-3 miles south of the U.S.-Mexico border to Fairbank, approximately 30 miles, and from the San Pedro River to the Huachuca Mountains, approximately 13 miles. Ground-water withdrawals within the study area are concentrated in the northwest portion of the modeled area around the City of Sierra Vista and its surrounding areas, and along the San Pedro River in the Palominas-Hereford area.

Model characteristics

In order to use MODFLOW the continuous natural system has to be replaced by a discrete set of cells in the three-dimensional space. Areally, the system is discretized into 18 rows and 35 columns (630 cells), with higher resolution where larger variations in aquifer properties and stresses occur. The grid is oriented in a southeastern-northwestern direction, paralleling the predominant river flow direction. This grid, originally designed by Freethey, was not intended to emphasize the river-aquifer system, but to prioritize the Sierra Vista area. Vertically, the aquifer system is represented by three layers. The first layer delineates the floodplain aquifer and extends along a narrow strip encompassing the San Pedro and Babocomari Rivers. The maximum width of the floodplain aquifer is 1 mile and its thickness ranges from 10 feet to 60 feet. The hydraulic conductivity of this layer is assumed to be 167 ft/day. The second layer represents that part of the basin fill deposits where data is available. The thickness of this intermediate layer ranges from a few feet at the basin boundary to 940 feet at the valley center. The hydraulic conductivity of the layer ranges from 18 ft/day to less than 3 ft/day. The lower most layer extends from 1,000 feet and below.

Recharge is simulated along the mountain front on the west and east sides of the modeled area. Evapotranspiration occurs along streams where shallow water tables are encountered. Therefore it is simulated in areas aligned with the San Pedro River and the Babocomari River, in coincidence with the alluvial aquifer.

Streams are represented by segments and reaches. The San Pedro River is divided into 33 river reaches, numbered from the uppermost upstream. Nine reaches form the Babocomari River, numbered with the same criteria. The San Pedro River width varies from 12 feet to 27 feet and a Manning's roughness coefficient of 0.020 is adopted.

Much of the data included in the model has been compiled by Freethey (1982). The new information gathered on stream characteristics has been partially provided by the Bureau of Land Management. The floodplain alluvial properties and extension have been defined based on well log data and available geologic maps.

The simulation process included a steady state and a transient analyses. Both simulations were intended to reproduce mean annual conditions:

Steady state simulation, or model calibration for pre-development conditions;

Transient simulation, or model calibration for development conditions.

Steady state simulation

Before 1940 pumpage in the Upper San Pedro Basin was almost negligible. Therefore, steady state conditions are assumed to exist prior to that year.

In terms of the ground-water system, a steady state water level contour map reconstructed by Freethey was used to compare simulated and observed water levels. The ground-water flow pattern is well represented. According to Freethey "the model calibration was considered acceptable when differences between model and field water levels were within +/- 25 feet because the contour map generated from field data was 50 feet".

In the new stream-aquifer module the streamflow at the first model reach of each river segment has to be specified. The San Pedro streamflow regime is highly variable on a seasonal and on a yearly basis. Based on an analysis of streamflows at different stations and for different time scales, the mean annual baseflow at Palominas was chosen to characterize the streamflow regime. Moreover, the model was aimed at analyzing the effect that pumping may have over streamflows. The use of the total streamflow, i.e. baseflow plus runoff, makes it difficult to determine up to what extent streamflows may be affected. In summary, the runoff component of the streamflow is not taken into account in the model.

Streamflows were used for model calibration. Simulated baseflows at Charleston were underestimated 25% with respect to estimated values provided by Korsten (1990). The use of baseflows results in an adequate choice to analyze the stream-aquifer interdependency. However, runoff volumes are an important component of the system mass balance. Runoff volumes recharge the floodplain alluvium after the hot season, which in turn, supply a portion of the water consumed by riparian vegetation. This water deficit in the model is compensated by reducing the evapotranspiration rate. Under this assumption, observed and estimated baseflows at Charleston differ only by about 2%. Water levels in the aquifer are just slightly affected.

The Arizona Department of Water Resources has estimated that under pre-development conditions 15,900 acre-feet per year migrated from the regional aquifer to the floodplain alluvial aquifer within the Sierra Vista Sub-basin. The simulated flow between these aquifers is 15,100 acre-feet per year. Recharge and discharge values from the model agree with conceptual model estimates given by Freethey. However, the Arizona Department of Water Resources provides very different values for evapotranspiration consumption under pre-development conditions. If one considers ADWR estimates the model is underestimating evapotranspiration.

Transient simulation

Model characteristics remained unchanged with respect to those of the steady-state simulation, only aquifer storage properties were added. Historical pumping data compiled by Freethey and later updated by ADWR have been used for the transient simulation. A total of twelve pumping or stress periods were defined, with a spatial pumping distribution concentrated in the Sierra Vista-Fort Huachuca-Huachuca City area and the Palominas-Hereford area. Ground-water withdrawals were different for each period, with a significant increasing trend.

Using the same procedure followed during the steady state analysis, model results were evaluated comparing simulated and observed values of water levels, streamflows and mass balance components.

Water-level contours maps reconstructed from field data (Roeske and Werrell, 1973; Koniezcki, 1980) were used to evaluate the transient response of the model. The model reproduces regional ground-water flow patterns. A comparison between water-levels for 1968 conditions and water-levels for 1988 conditions shows that the cone of depression in the Sierra Vista area has expanded. This fact had already been reported by Putman et al.(1988).

The San Pedro River is mainly a gaining river, except along some reaches around Palominas and downstream of the Charleston Bridge. One way to evaluate the effect of pumping over the river-aquifer interaction process is by means of a losing/gaining stream reaches analysis for different stress periods. A gaining reach is that portion of the stream that gains water from the aquifer, on the contrary a losing reach is that portion of the stream that loses water to the aquifer. The analysis indicates that, as pumping increases, losing reaches in the Palominas area lose more water to the aquifer and gaining reaches downstream gain less water from the

ground-water system. On the other hand model results show a decrease in the amount of water migrating from the regional aquifer to the floodplain aquifer over time. These two effects (decreasing upward flow and changes experienced along losing/gaining reaches) indicate how, in some way or another, ground-water withdrawals can affect low streamflows in the streams. Wells located far from the stream may alter the regional ground-water flow, intercepting a portion of the recharge that otherwise would find its way to the streams. Wells located in the proximities of the streams may affect the streamflows more directly due to its geographic location close to a capture source.

Baseflows calibration using the evapotranspiration rate set in Freethey's model was partially successful. Simulated baseflows differed from observed values by more than 100 % during certain stress periods. Following the same criteria outlined for the steady state analysis, the streamflows calibration was improved when the evapotranspiration rate was adjusted. Even though the baseflows fitting improves, by the end of the simulation period simulated baseflows are still underestimated with respect to calculated ones. The adjustment of the evapotranspiration rate to partially compensate runoff volume deficits is not enough to get a closer matching.

Conclusions and recommendations

The results of the present study were briefly discussed in previous sections. A complete report that covers all aspects of the study is about to be completed and submitted to the Upper San Pedro Water Management Council, Technical Sub-committee.

The model just developed provides a reasonable tool to be used in exploring future scenarios of development within the study area. The transient model calibration reflects the model response to the particular historical pumping that took place in the area (ADWR data) up to 1988. No future predictions were attempted.

The basis of this model was originally developed to reproduce global ground-water patterns within the study area, in particular around population concentrations. Consequently, the design of the grid responds to that conception and does not emphasize the river system. The stream-aquifer module implemented into the model brought some new insights about the river-aquifer interaction process that were partially addressed in previous studies. A higher performance of this new module, and hence of the model as a whole could be achieved if the model grid is refined along the stream-alluvial system.

The conclusions outlined previously in terms of runoff volume deficits in the model open the debate in terms of the necessity to incorporate the runoff component into the model. A reduction of the time scale certainly would allow the simulation of seasonal processes such as the evapotranspiration and the streamflow regime. Even though this appears to be a reasonable choice, data availability particularly in terms of pumping, can make that alternative difficult to implement.

Most of the aquifer parameters data was compiled by previous authors. The properties of the floodplain aquifer, the layer added during the present study, were defined based on reported values for alluvial basins in the southwest and some estimates provided by the ADWR. The model performs correctly with the present assumptions, but field measurements will help to confirm or correct present estimates.

The historical pumping data used for the study were updated and provided by the ADWR. The ADWR closely reviewed pumping figures for municipal and industrial uses. Agricultural pumping was also given some consideration. Due to its importance as a major user and the proximity of irrigation wells to the streams, a revision of the amount of water being pumped for agriculture should be undertaken. As of now, pumping data for irrigation has been reduced a certain percentage to account for return flows. It may be useful in the future to break down both components, pumping and return flows, and incorporate them into the model.

Water level monitoring at selected wells was performed by the ADWR in 1989 and a water-level contour map was constructed. The USGS also conducts monitoring activities within the study area. If these monitoring well activities are performed regularly, that information, along with reported pumpind data, will be really valuable for future model updates.

Since 1987, the Bureau of Land Management collects streamflow data at 5 locations within the study area. The BLM streamflow monitoring program should be revised to provide measurements of streamflows on a consistent time basis. The streamflow record is still too short, but the data from those stations will constitute a valuable source of information for future model calibration. Determination of rating curves will also provide useful information for model calibration and validation. Surveying stream cross-sections at selected spots will result in a better definition of geometric parameters as well as streambed characteristics.

WATERBUD

Introduction

WATERBUD is a model of the water balance in the Upper San Pedro River basin in southeastern Arizona. The model consists of a spreadsheet written for use with LOTUS 1-2-3, Release 3. The model allows users to examine how hydrologic, demographic, climatic, and economic conditions, and water management policies may affect the balance in the basin over the next twenty years.

The model treats the upper basin as consisting of a Mexican sub-basin and two sub-basins in the U.S., each containing a portion of the basin-fill and alluvial aquifers and a reach of the river. The calculations attempt to account for all waters entering and leaving the basin, including storm precipitation and runoff. Separate, detailed documentation provides instructions on use of the model. Users should be familiar with the operation of LOTUS 1-2-3 or a similar spreadsheet program.

The model has two sections: The first section, called the Parameters section, specifies a set of initial or "default" conditions, which together characterize the water balance in the upper basin. Specifically, the parameters help characterize the movement of water to and from municipal, industrial, and agricultural users, natural ecosystems, the upper basin's two aquifers, and the river. This section of the model allows the user to specify a wide range of alternative initial conditions, such as alternative population growth rates or crop irrigation requirements, to see how these conditions affect the overall water balance.

The initial conditions come in two varieties: (1) parameters that help describe the characteristics of the upper basin in the years 1989-1990; and (2) parameters that help describe how these characteristics will change during a simulated 20-year sequence from 1991 to 2010. The default settings that describe conditions in 1989-1990 are based on extensive documentation, and on comparisons of 1989-1990 hydrologic data against the results of trial runs of the model. Appendix B lists the parameters as they appear in the spreadsheet; the reader should consult the complete documentation for the model, for information on specific settings.

The second section, called the Projections section, contains equations that simulate the water budget of the upper basin for a twenty-year period based on the initial conditions. Each simulated "year" contains four seasons, for which the equations generate information on the flow of water to and from the regional aquifer, the floodplain aquifer, and the river in each of the two U.S. sub-basins. Appendix C lists the variables, for which the model generates projections by season or by year. The reader should consult the detailed documentation, for information on the construction of all equations.

WATERBUD examines the water budget or mass balance of water in the Upper San Pedro River basin. A water budget consists of an accounting of the water entering and leaving a hydrologic system, and the quantity of water stored in the system. Any difference between the quantity of water entering versus leaving a system must result in a change in the quantity of water stored: If more water enters than leaves, storage increases; if more water leaves than enters, storage decreases.

The Upper San Pedro basin has water stored in two aquifers: a regional aquifer consisting of basin fill deposits of compacted and cemented gravels, sands, silts, and clays; and a zone of younger alluvial deposits variously known as the inner valley, younger alluvial, or floodplain aquifer (Roeske and Werrell, 1973; ADWR, 1990). Bedrock underlies the regional aquifer and some sections of the floodplain aquifer.

The natural water budget of the regional aquifer is quite simple. Water enters the regional aquifer almost entirely as a result of the infiltration of snowmelt and rainfall runoff along the faces of the mountains that ring the basin. Most of this water eventually (although very slowly) moves from the regional to the floodplain aquifer. Small amounts emerge at springs at the base of the mountains, are removed through evaporation and vegetative transpiration, or contribute to a slight northward flow of groundwater within the regional aquifer alone.

The natural water budget of the floodplain aquifer is more complex. Water enters the floodplain aquifer in two ways, from the regional aquifer and from the river. The natural flow from the regional aquifer into the floodplain aquifer is roughly constant year-round. It results from the fact that a large quantity of the water in the regional aquifer stands at a higher elevation than the water in the floodplain aquifer. The flow between the river and the floodplain aquifer is more variable.

When flow in the river increases, the level (stage) of water in the river may rise above the water table in the floodplain aquifer alongside the river, and water then seeps from the river into the aquifer. When flow in the river decreases, the level (stage) of water in the river may fall below the water table in the floodplain aquifer alongside the river, and water then seeps from the aquifer into the river.

The floodplain aquifer also loses large quantities of water to vegetative transpiration (phreatophyte consumption). Smaller quantities evaporate from bare ground, especially along exposed portions of the streambed, or contribute to a slight northward flow of water within this aquifer as well.

The third major natural component of the hydrologic system is the river itself. The San Pedro River receives water from two sources: runoff from snowmelt and rainfall, and discharges from the floodplain aquifer. Only a small portion of the basin's runoff ever reaches the river; most evaporates or infiltrates long before it reaches even an ephemeral stream channel. The discharges from the aquifer produce what is termed the baseflow of the river; runoff produces

storm flows. Most water in the river leaves the upper basin as downstream flow, but some seeps into the floodplain aquifer (as noted above) and a small portion simply evaporates. The Babocomari River behaves hydrologically similarly to the San Pedro River, and eventually contributes its flows to the San Pedro River.

WATERBUD carries out an accounting of all of these flows into and out of the two aquifers and the river. These flows depend on such factors as precipitation and evaporation rates, vegetative transpiration rates, hydraulic properties of the aquifers and the riverbed, and differences in water levels and pressures (together known as hydraulic head) among the two aquifers and the river in each sub-basin.

Human use of water in the upper basin results in additional losses and gains in the overall water budget. The WATERBUD model classifies human activities as domestic (including municipal), industrial, and agricultural. Each of these kinds of activities involves the removal of water from one or both of the aquifers and, in the case of agriculture, directly from the river as well.

A portion of the water diverted for domestic use leaves the basin by evaporation and vegetative transpiration, especially from irrigated fields, orchards, gardens, recreational facilities, and yards. The remaining water, after use, becomes wastewater that flows into septic tanks or sewers; sewerage goes to wastewater treatment plants. All wastewater treatment plants in the upper basin presently allow their treated effluent to evaporate from the treatment facilities or from fields irrigated with the treated water.

In the future, treated effluent may also be pumped or infiltrated into the ground, to recharge the groundwater supply. Septic tank water already infiltrates. Domestic consumption rates vary, depending on such factors as the costs of delivered or pumped water, household size and income, plumbing codes, and water conservation practices.

Different mining and other industrial activities require varying quantities of water. Some of the used water may infiltrate into the ground from settling and other treatment ponds; the rest evaporates. Settling ponds for mining leachates in particular are not allowed to infiltrate their treated waters; all is lost to evaporation. Industrial demands for water vary with economic conditions in the basin, such as the need for sand and gravel in construction, and with the global market for nitrate products or the metals mined in the area.

Irrigation consumes by far the greatest quantity of agricultural water in the upper basin. Water pumped from wells and diverted from the river goes to prepared fields, where it supplements the scant water provided by precipitation or available from the immediate water table. As in most of the Southwest, potential evapotranspiration in the upper basin greatly exceeds actual precipitation, making irrigation necessary for virtually all crops. Some water evaporates or infiltrates from the ditches used to bring the water to the fields. A large portion of the water finally delivered to the irrigated fields leaves through vegetative transpiration; the rest either evaporates directly or infiltrates back into the groundwater supply.

Irrigators also must flush their fields regularly to remove salts, which exist naturally in the groundwater and become concentrated in the soil by evaporation of the irrigation water. The ratio of the water consumed by crop transpiration and soil flushing, to the total amount of water sent out to fields, is termed the irrigation efficiency. Irrigation demands for water vary with seasonal precipitation, air temperatures, crop types, and irrigation efficiencies.

Stockponds and reservoirs in the upper basin also consume water. These impoundments exist primarily to serve livestock. However, much of the impounded water evaporates, most of the remainder leaves as spills and infiltration, and only a very small portion actually goes into the livestock themselves.

WATERBUD carries out an accounting of all known or reasonably expectable human impacts on the flow of water into and out of the two aquifers and the river. As noted above, human impacts on the upper basin's water budget depend on the interplay of many different factors. WATERBUD provides means for examining the effects of changing the strength of many of these factors. For example, users of the model can examine the effects of increasing the delivery price of domestic water, or improving irrigation efficiencies. WATERBUD also provides means for simulating other kinds of impacts, such as the effects of cloud seeding or water imports.

WATERBUD thus acts as a large ledger. It tallies up the gains and losses of water for the two aquifers and the river, that arise both through natural processes and human activities in the upper basin. The water balance calculated for the end of each season provides the input for the next season's calculations. The results of the calculations for each season and for each year overall are stored in the spreadsheet for later analysis.

Table 4 presents a summary of the major components of the water budget for the upper basin in 1988-89 as computed by WATERBUD. (The values differ slightly from those presented by the ADWR in the Hydrographic Survey Report, Table 4-14. See the report accompanying this model for a complete description of operating assumptions.)

TABLE 4
Summary Annual Water Budget as Computed by WATERBUD
1988-1989 Development Conditions, by Sub-basin
(quantities are in acre feet)

Sub-basin:	Sierra Vista	Benson
Regional Aquifer		
Underground Inflow	+2100	0
Natural Recharge	+13860	+11760
Irrigation Depletion	0	0
Domestic/Municipal Depletion	-10817	-1011
Stockpond&ReservoirDepletion	-14	-21
Industrial Depletion	-104	-379
Underground Northward Outflow	0	0
Discharge to Floodplain Aquifer	-27426	-9587
Floodplain Aquifer		
Underground Inflow	+900	0
Recharge from Regional Aquifer	+27426	+9587
Irrigation Depletion	-14357	-11552
Domestic/Municipal Depletion	0	0
Industrial Depletion	0	0
Phreatophyte Consumption	-14500	-18619
Underground Northward Outflow	0	-120
Leakage to(-) or from(+) River	+531	+20704
Surface Water Flows		
River Inflow	+23420	+39190
Tributary Stream Inflow	+19472	+14843
Evaporation of Runoff for Stockponds	-1888	-1217
River Channel Evaporation	-1291	-622
Irrigation Ditch Diversions from River	0	-5989
Leakage to(-)/from(+) Floodplain Aquifer	-531	-20704
River Outflow	-39190	-25500
Net Changes in Storage		
Gain(+) or Loss(-) in Regional Aquifer	-2240	+762
Gain(+) or Loss(-) in Floodplain Aquifer	0	0

WATERBUD Results

WATERBUD analyses were carried out, in order to examine the five scenarios and five policy options described earlier in this report. The results of these simulations are summarized in Table 5 and in Figures 4 through 21. Each policy option was examined under two conditions: the "normal" conditions for population growth, climate, and agricultural growth, as specified in Scenario A ; and the sustained severe drought conditions as specified in Scenario D.

The results of the WATERBUD analyses are strongly shaped by four key assumptions. Changing any one of these assumptions could change the results of the analyses. These four assumptions are as follows: (1) The data on average annual mountain-front recharge, effective irrigated acreage, irrigation efficiencies, and crop irrigation requirements presented in the Arizona Department of Water Resources, 1990 Preliminary Hydrographic Survey Report, are taken to be correct. (2) Discharges from the regional aquifer to the floodplain aquifer up to 1988-1989 are assumed to have been sufficient to sustain a stable water table in the floodplain aquifer up to that time. (3) The preliminary U.S. Census figures for 1990 are taken to be correct, for purposes of modeling population sizes and growth rates. (4) The pattern of water consumption at Fort Huachuca is assumed to be unaffected by any of the policy options examined in this study. The effects of the first two assumptions are closely linked.

The reader also should note that the WATERBUD simulations handle Scenario D in a different manner than do the MODSIM simulations. In the MODSIM analyses, a ten-year cycle of actual precipitation and streamflow data was run twice in succession, to produce a simulated twenty-year climate record. The ten-year period selected for this purpose exhibited conditions consistently drier than normal. The WATERBUD analyses for Scenario D examine climatically more stressful conditions. It defines a severe-case year, during which precipitation is 27.5% lower than normal, and evaporation rates are 10% higher than normal as a consequence of higher temperatures. This severe-case year is then repeated twenty times, to produce a twenty-year sequence of sustained, severe drought. As a result, Scenario D in the WATERBUD analyses entails a more severe and more sustained drought than does Scenario D in the MODSIM analyses.

Table 5 summarizes the results of the WATERBUD analyses. It shows the projected consequences of each of the five policies for storage in the regional and floodplain aquifers, and for the flow of the San Pedro river as it leaves each sub-basin. The table first lists the estimates for aquifer storage and river flow under a "normal" climate; these provide the starting point for Scenarios A, C, and E. The table next lists the estimates for aquifer storage and river flow under a "severe drought"; these estimates provide the starting point for Scenarios B and D. Finally, the table lists the results for the actual analyses. The starting year for all analyses is referred to as "1990."

Table 5

SUMMARY OF WATERBUD RESULTS
PROJECTED CUMULATIVE EFFECTS OF ALTERNATIVE POLICIES AFTER TWENTY YEARS, RELATIVE TO 1990 CONDITIONS

	Regional Aq. Sierra Vista Sub. (acre feet)	Floodplain Aq. Sierra Vista Sub. (acre feet)	San Pedro River Sierra Vista Sub. (acre-feet/year)	Regional Aq. Benson Sub. (acre feet)	Floodplain Aq. Benson Sub. (acre feet)	San Pedro River Benson Sub. (acre-feet/year)
1990, "Normal" Conditions	31730841	159609	39190	27065444	123681	25500
1990 Effect of Simulated Drought	-4859	0	-20723	-20511	0	-16655
TWENTY-YEAR EFFECTS OF POLICY 1						
Scenario A	-486550	-3328	-368	13675	-67	51
Scenario B	-826743	-11348	-21020	-614931	-14608	-16602
Scenario C	-560662	-3676	-368	9656	-85	51
Scenario D	-587657	-5321	-20911	-408764	-7780	-16538
Scenario E	-627445	-8264	-405	-163616	-5948	14
TWENTY-YEAR EFFECTS OF POLICY 2						
Policy 2-1, Scenario A	-382602	-1815	-205	118168	1870	1577
Policy 2-1, Scenario D	-471397	-3538	-20900	-257810	-4916	-16527
Policy 2-2, Scenario A	-247379	237	-7	197718	3194	3927
Policy 2-2, Scenario D	-343961	-1018	-20789	-125165	-2576	-16652
Policy 2-3, Scenario A	-169651	2203	412	216808	5282	6995
Policy 2-3, Scenario D	-219549	1249	-20476	8257	-33	-16617
TWENTY-YEAR EFFECTS OF POLICY 3						
Policy 3-1, Scenario A	-160489	2186	413	223448	6229	6762
Policy 3-1, Scenario D	-204692	1341	-20480	14828	8	-16616
Policy 3-2, Scenario A	-135503	2393	403	225429	6399	6921
Policy 3-2, Scenario D	-183275	1480	-20485	16755	19	-16615
Policy 3-5, Scenario A	-105772	2606	393	227762	6468	6986
Policy 3-5, Scenario D	-155112	1663	-20492	19017	32	-16613
Policy 3-10, Scenario A	-87135	2732	387	229193	6481	6998
Policy 3-10, Scenario D	-137025	1778	-20497	20683	42	-16639
TWENTY-YEAR EFFECTS OF POLICY 4						
Scenario A	-387232	-2767	-368	43633	233	67
Scenario D	-488051	-4694	-20904	-378648	-7537	-16532
TWENTY-YEAR EFFECTS OF POLICY 5						
Scenario A	-362777	-1688	-206	123739	1898	1604
Scenario D	-451678	-3413	-20900	-251816	-4881	-16527

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Each analysis projects the conditions likely to exist after each of the next twenty years, for a given a combination of a particular scenario and a particular policy option. The results are also summarized graphically in Figures 4 through 21. The following paragraphs summarize the results of the WATERBUD analyses.

Policy 1

The five scenarios have different effects on the conditions projected to exist after 20 years under Policy 1, and these effects also differ between the two sub-basins. Table 1 and Figures 4 through 9 illustrate these effects. Population growth (Figure 4) is greatest in Scenarios B and C; however, ratio of urban to rural population changes little. Storage in the floodplain aquifer (Figure 5) declines in the Sierra Vista sub-basin under all five scenarios; taken alone, agricultural growth has the greatest impact, followed closely by drought conditions.

By comparison, storage in the floodplain aquifer in the Benson sub-basin does not suffer from local population growth and is more severely reduced by drought conditions rather than by agricultural growth. It should be noted that population growth rates are low in the Benson sub-basin even under the worst-case conditions projected in Scenarios B and C. Population growth in the Sierra Vista sub-basin (Figure 6) reduces storage in the regional (basin fill) aquifer almost as severely as does a prolonged drought or agricultural growth. In turn, storage in the regional aquifer in the Benson sub-basin does not suffer from local population growth and is much more severely reduced by drought conditions than by agricultural growth.

Annual river discharges (Figure 7) suffer most severely under a severe drought in both sub-basins; neither population growth nor agricultural growth has much impact on river discharges. All five scenarios result in slight reductions in riparian vegetation acreage in both sub-basins (Figure 8), with agricultural growth having the greatest impact. It should be noted that agricultural growth is assumed to involve the expansion of irrigation to lands away from the river that are not presently either farmed or protected as riparian reserves.

Consequently, the decline in riparian acreage forecast under the five scenarios results from reductions in water tables and streamflows, which then together cause damage to the existing riparian stands. It should also be noted that only Scenarios B and E involve increases in irrigated acreage (Figure 9). Finally, median household income (not illustrated) does not change under any of the five scenarios.

Floodplain Aquifer Storage under Policies 2, 3, 4, and 5

Policy options 2, 3, 4, and 5 also have quite different effects on storage in the floodplain aquifer. These effects again differ between the two sub-basins, and also differ between normal

and drought condiions (Figures 10-11). Drought conditions have a greater impact on floodplain aquifer storage in the Benson sub-basin than in the Sierra Vista sub-basin.

Policies 2-1 to 2-3 have increasingly positive effects on reducing losses to storage in the floodplain aquifer. Under normal conditions, these policies result in gains to storage in the floodplain aquifer in both sub-basins. Under drought conditions, these policies reduce the rate of loss to floodplain storage, but produce a gain to storage only under Policy 2-3 and then only in the Sierra Vista sub-basin.

Policy 3 results in gains to storage in the floodplain aquifer under all conditions in the Sierra Vista sub-basin, and under normal conditions in the Benson sub-basin. It nearly but not quite completely eliminates losses to floodplain aquifer storage in the Benson sub-basin under drought conditions.

Policies 4 and 5 result in gains to storage in the floodplain aquifer in the Benson sub-basin only under normal conditions; they are highly ineffective under drought conditions in this sub-basin, and have only moderately positive effects in the Sierra Vista sub-basin under any conditions.

Regional Aquifer Storage under Policies 2, 3, 4, and 5

Policy options 2, 3, 4, and 5 have different effects on storage in the regional aquifer; these effects differ between the two sub-basins, and between normal and drought conditions (Figures 12-13). Drought conditions have a greater impact on regional aquifer storage in the Benson sub-basin than in the Sierra Vista sub-basin.

Policies 2-1 to 2-3 again have increasingly positive effects in reducing losses to storage in the regional aquifer. Under normal conditions these policies result in gains to storage in the Benson sub-basin and reduced losses in the Sierra Vista sub-basin. However, under drought conditions these policies can only reduce the rate of loss in either sub-basin. Only Policy 2-3 results in a gain to regional aquifer storage in either sub-basin, specifically a very slight gain in the Benson sub-basin alone.

Policy 3 results in gains to storage in the regional aquifer in the Benson sub-basin under all conditions, although the amount of this gain is quite small under drought conditions. Policy 3 reduces but does not eliminate the losses to storage in the Sierra Vista sub-basin under all conditions. Policies 4 and 5 result in gains to storage in the regional aquifer in the Benson sub-basin under normal conditions. However, Policies 4 and 5 have little effect on regional aquifer storage in the Benson sub-basin under drought conditions, and have little effect on regional aquifer storage in the Sierra Vista sub-basin under any conditions.

River Discharges under Policies 2, 3, 4, and 5

Policy options 2, 3, 4, and 5 have different effects on river discharges from the two sub-basins (Figures 14-15). None of the policies has much impact on discharges from the Sierra Vista sub-basin under either normal or drought conditions, nor any impact on discharges from the Benson sub-basin under drought conditions. However, Policy 3 in general, and the stronger variants of Policy 2, result in increased discharges from the Benson sub-basin at least under normal conditions. These positive effects in the Benson sub-basin probably result from projected curtailments in irrigation pumping coupled with the low rate of population growth in the sub-basin. Policies 4 and 5 have little impact on river discharges under any conditions in either sub-basin.

Riparian Acreage under Policies 2, 3, 4, and 5

WATERBUD is designed to simulate changes in riparian acreage that could result from changes in river discharges or from changes in irrigated acreage. Specifically, increases in riparian acreage should result from any combination of increased river discharges and the retirement of agricultural land. This pattern is evident in the results of the simulations (Figures 16-17).

In particular, the policies that allow river discharges to increase (Policies 2, 3, and 5 for the Benson sub-basin; Policies 2 and 3 in the Sierra Vista sub-basin) also allow an increase in riparian vegetation, although these effects are more pronounced in the Benson sub-basin than in the Sierra Vista sub-basin. Policies 2 and 3 allow river discharges to increase even under drought conditions, when compared to the effects of having no management policy at all (Policy 1).

These same policies allow riparian vegetation to do better than would be the case without any management policy at all, under those same drought conditions. However, the beneficial effects of Policies 2 and 3 under drought conditions are slight; readers should note the difference in scale between Figures 16 and 17.

Irrigated Acreage under Policies 2, 3, 4, and 5

Policies 2, 3, 4, and 5 have nearly identical effects on the total acreage of irrigated lands under all conditions (Figures 18-19). Acreage declines markedly under Policy 2, as is the policy's intent, and declines slightly under Policy 3.

The declines under Policy 3 are somewhat larger in the Benson sub-basin under drought conditions. The declines under Policy 3 all result from allowing riparian vegetation to reclaim previously irrigated lands.

Median Household Income under Policies 2, 3, 4, and 5

Policies 2, 3, 4, and 5 also have identical effects on median household income, under all conditions (Figure 20). Median household income for the entire upper basin improves (if only slightly) only under Policy 2. Policy 3 results in progressively larger declines in median household incomes as the water surcharge increase, as a result of the financial burden imposed by the charges. Policy 4 has no effect on median household income, while Policy 5 results in a slight decline as a result of its imposition of stringent conservation measures.

Summary of WATERBUD Results

In general, policies that reduce agricultural consumption have the largest single beneficial effects on the overall water balance. These beneficial effects are achieved primarily through pumping surcharges or the actual retirement of irrigated land. The beneficial effects include increased storage in the floodplain aquifer and stable or increased river discharges, which in turn encourage the growth of riparian vegetation.

Increased storage in the floodplain aquifer also results in reduced discharges from the regional (basin fill) to the floodplain aquifer, which helps reduce the losses to storage in the regional aquifer. However, modifying agricultural activities alone does not eliminate the drawdowns to storage in the regional aquifer. The regional aquifer is under far more stress in the Sierra Vista sub-basin than in the Benson sub-basin, due to the higher population size and higher population growth rates in the Sierra Vista area. Losses to storage in the regional aquifer, in the Sierra Vista sub-basin, are reduced only through municipal water conservation in this sub-basin, although none of the policies examined appears capable of completely eliminating these losses. Drawdowns of the regional aquifer in the Sierra Vista sub-basin thus comprise the most intractable problems identified by the WATERBUD simulations, under all scenarios and policy options.

Figure 4

Total Urban and Rural Populations After 20 Years
Under Different Scenarios, by Sub-basin
(with 1990 Populations Shown for Comparison)

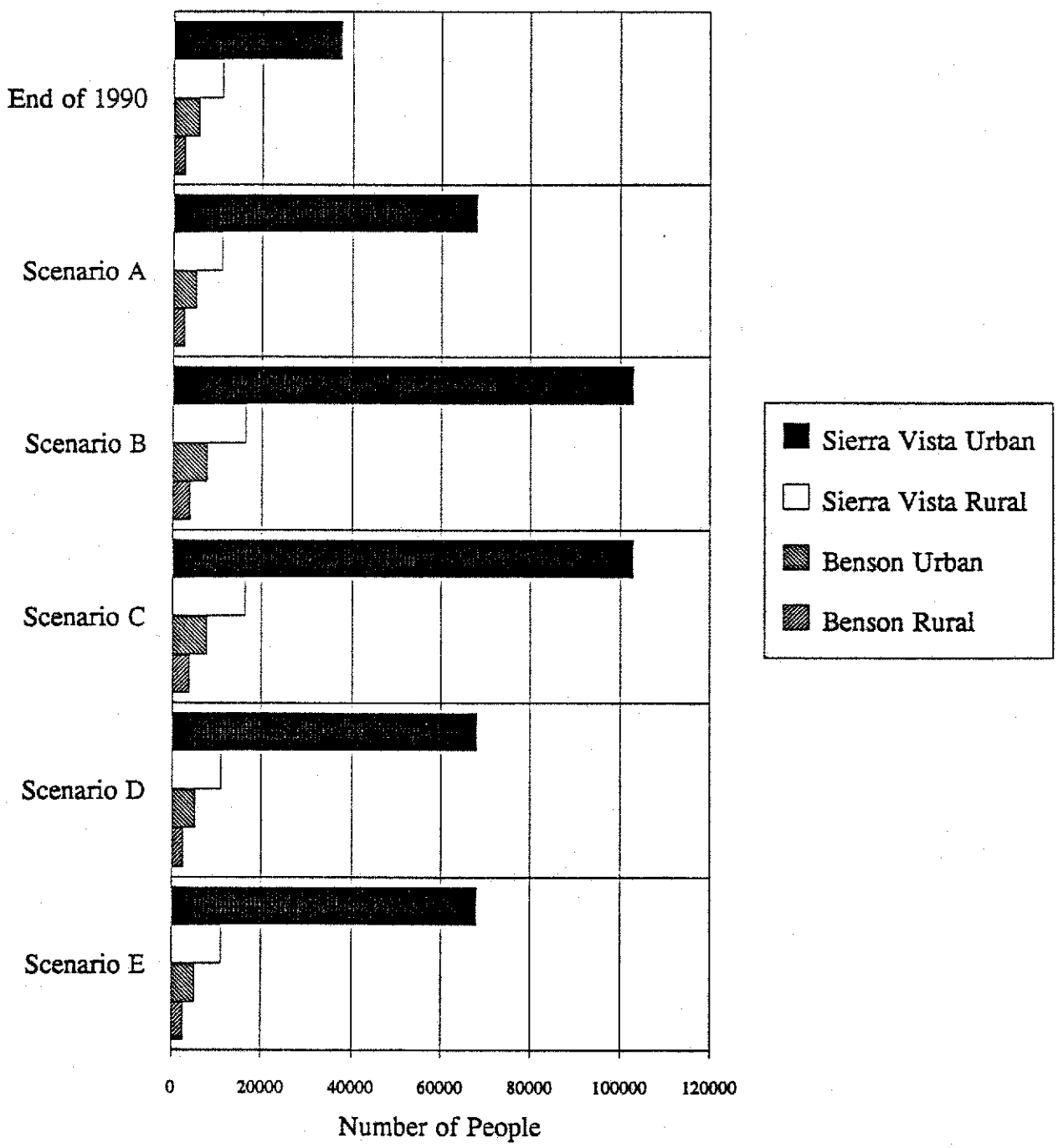


Figure 5

Cumulative Change in Floodplain Aquifer Storage After 20 Years
Under the Different Scenarios, by Sub-basin

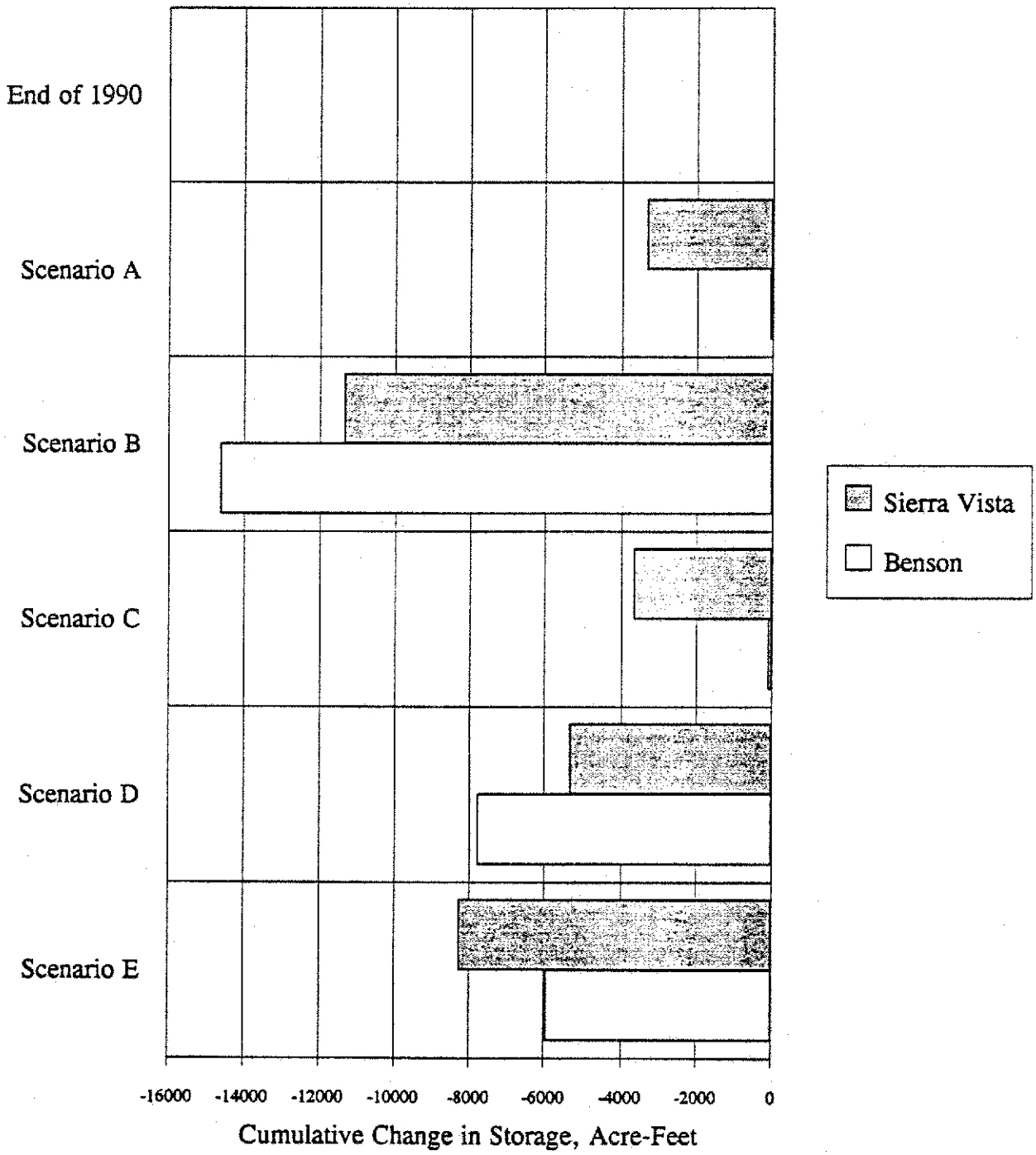


Figure 6

Cumulative Change in Regional Aquifer Storage After 20 Years
Under the Different Scenarios, by Sub-basin

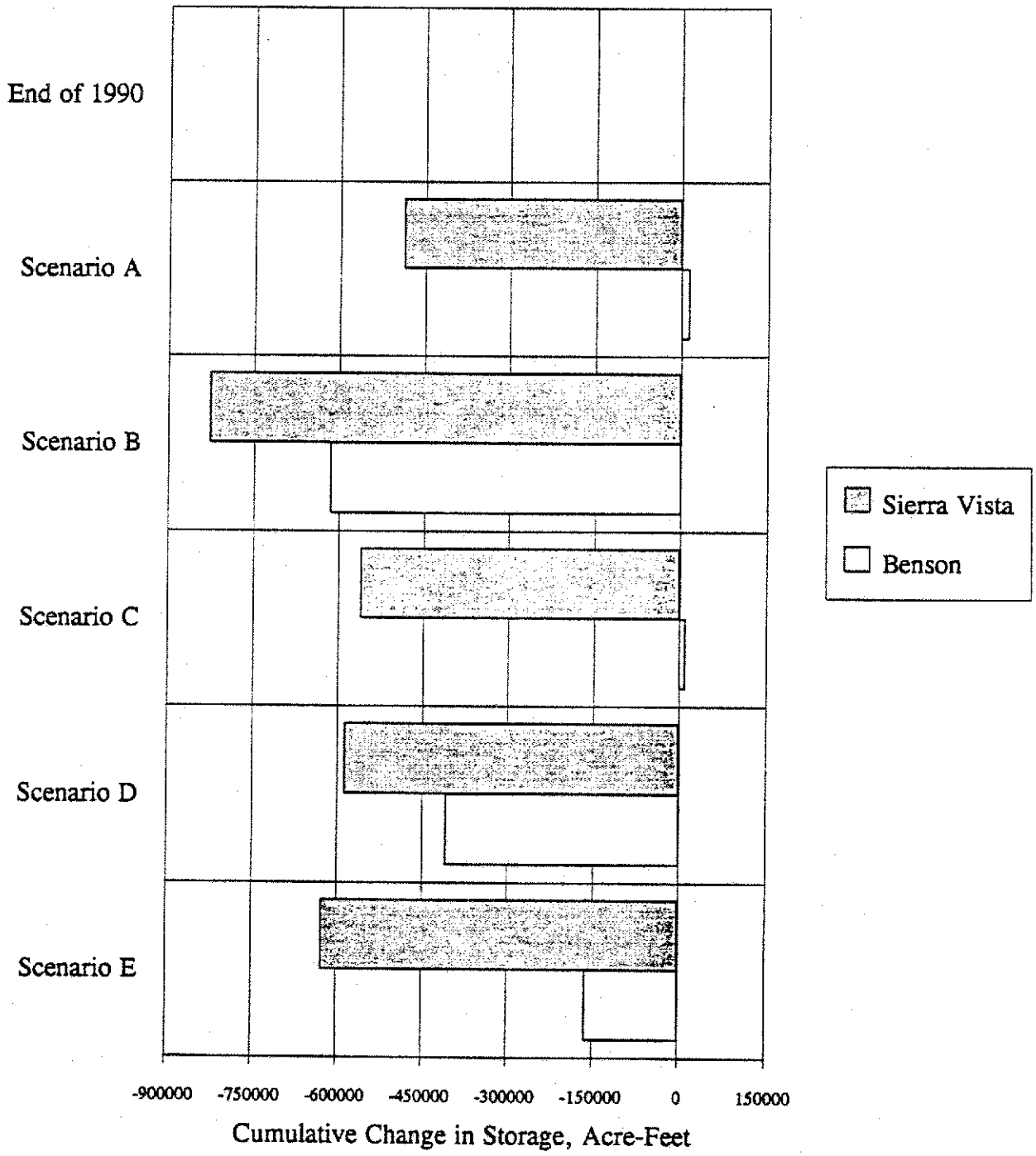


Figure 7

Annual Discharge of San Pedro River After 20 Years
Under the Different Scenarios, by Sub-basin

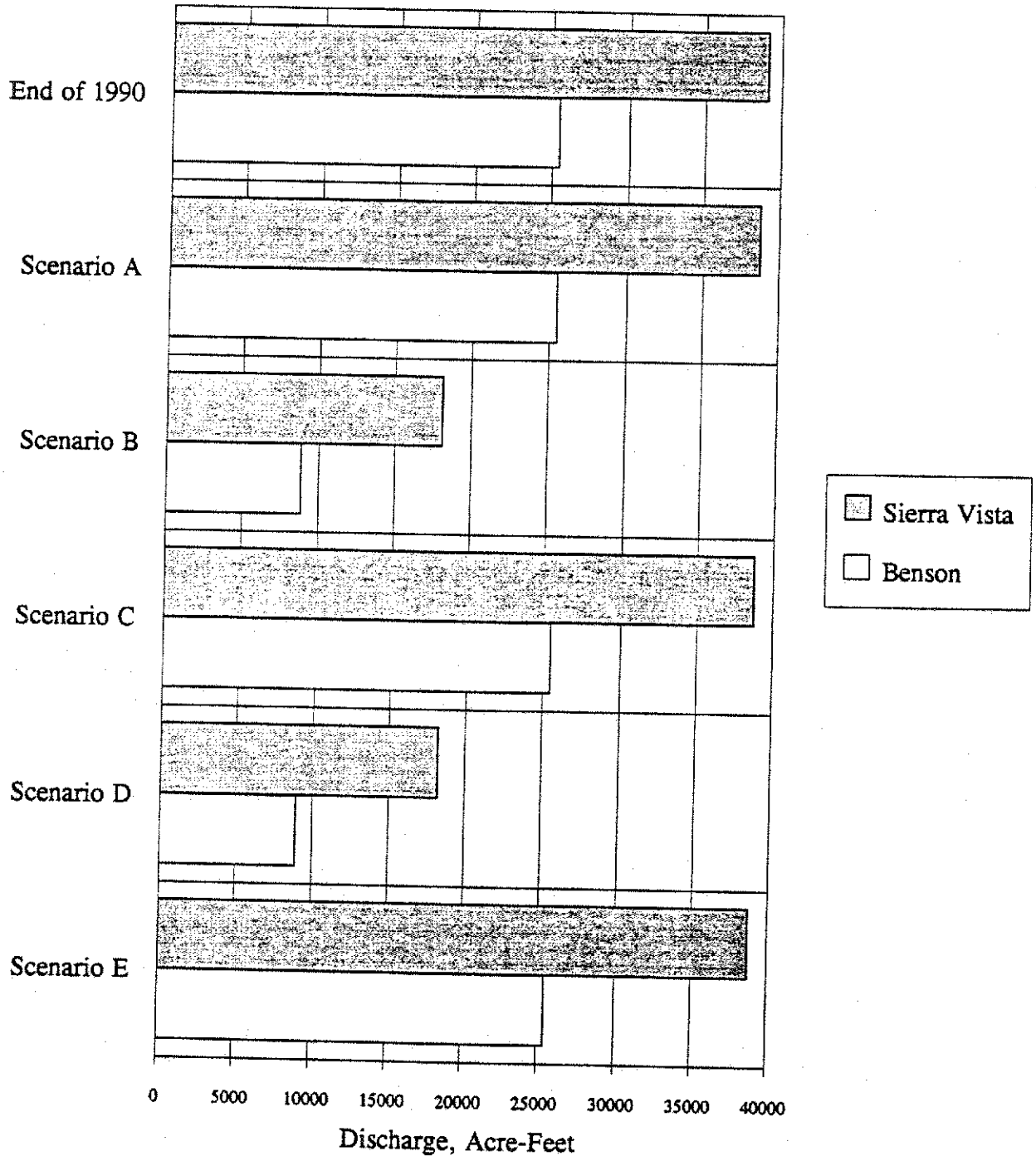


Figure 8

Cumulative Change in Area of Riparian Vegetation After 20 Years
Under the Different Scenarios, by Sub-basin

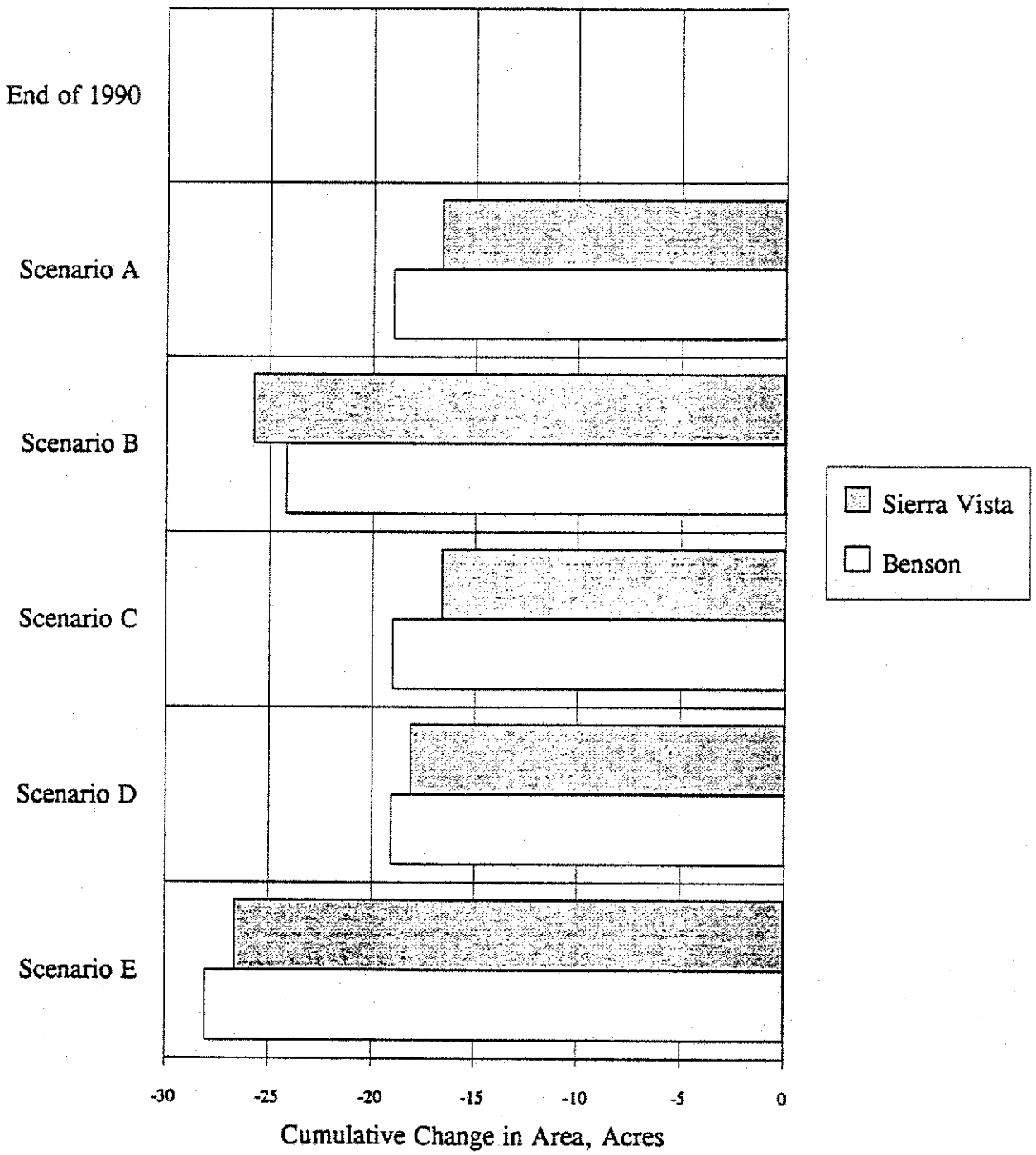


Figure 9

Cumulative Change in Effective Irrigated Acreage After 20 Years
Under the Different Scenarios, by Sub-basin

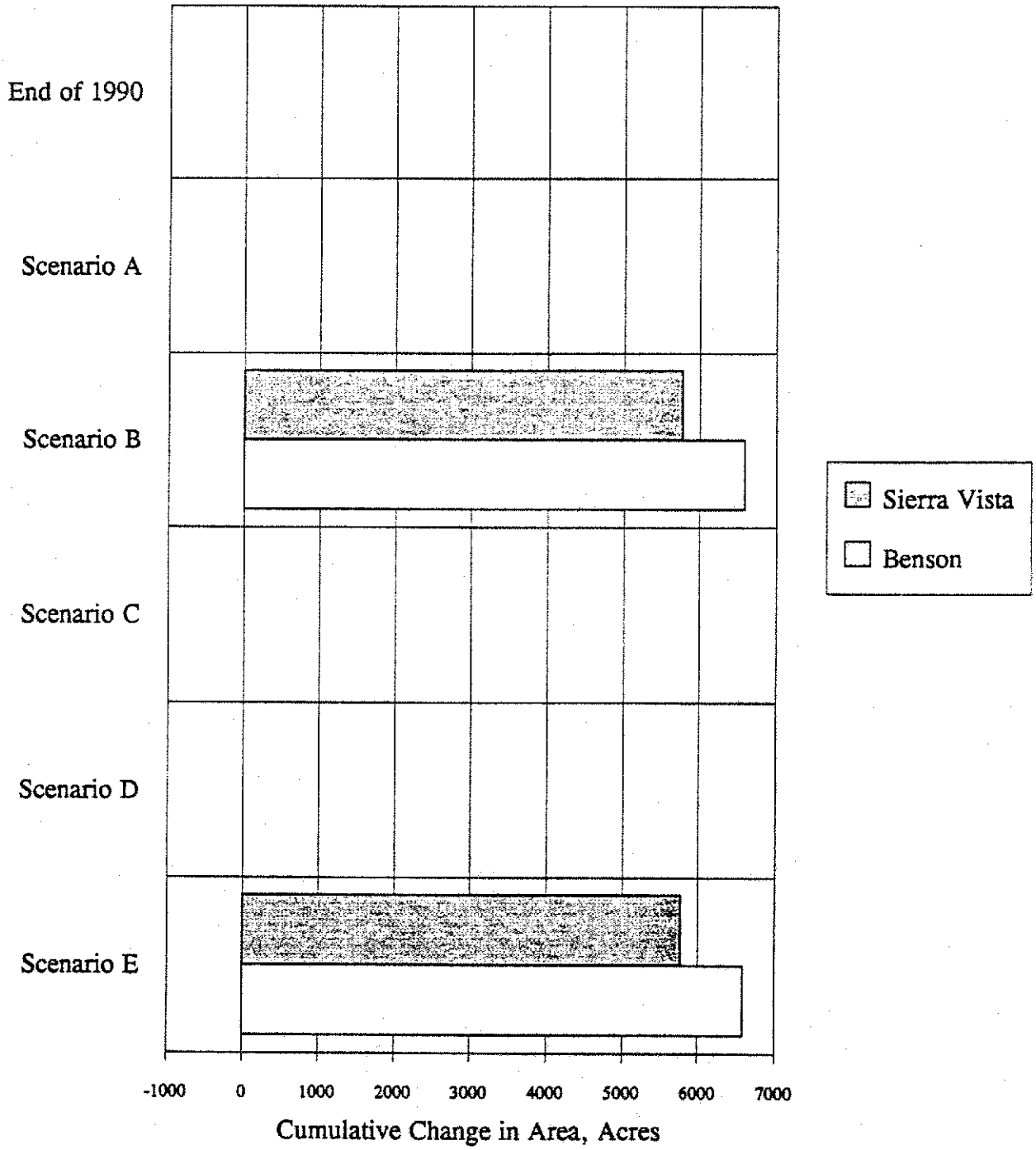


Figure 10

Cumulative Change in Floodplain Aquifer Storage After 20 Years
Under Different Policies and Scenario A Conditions, by Sub-basin

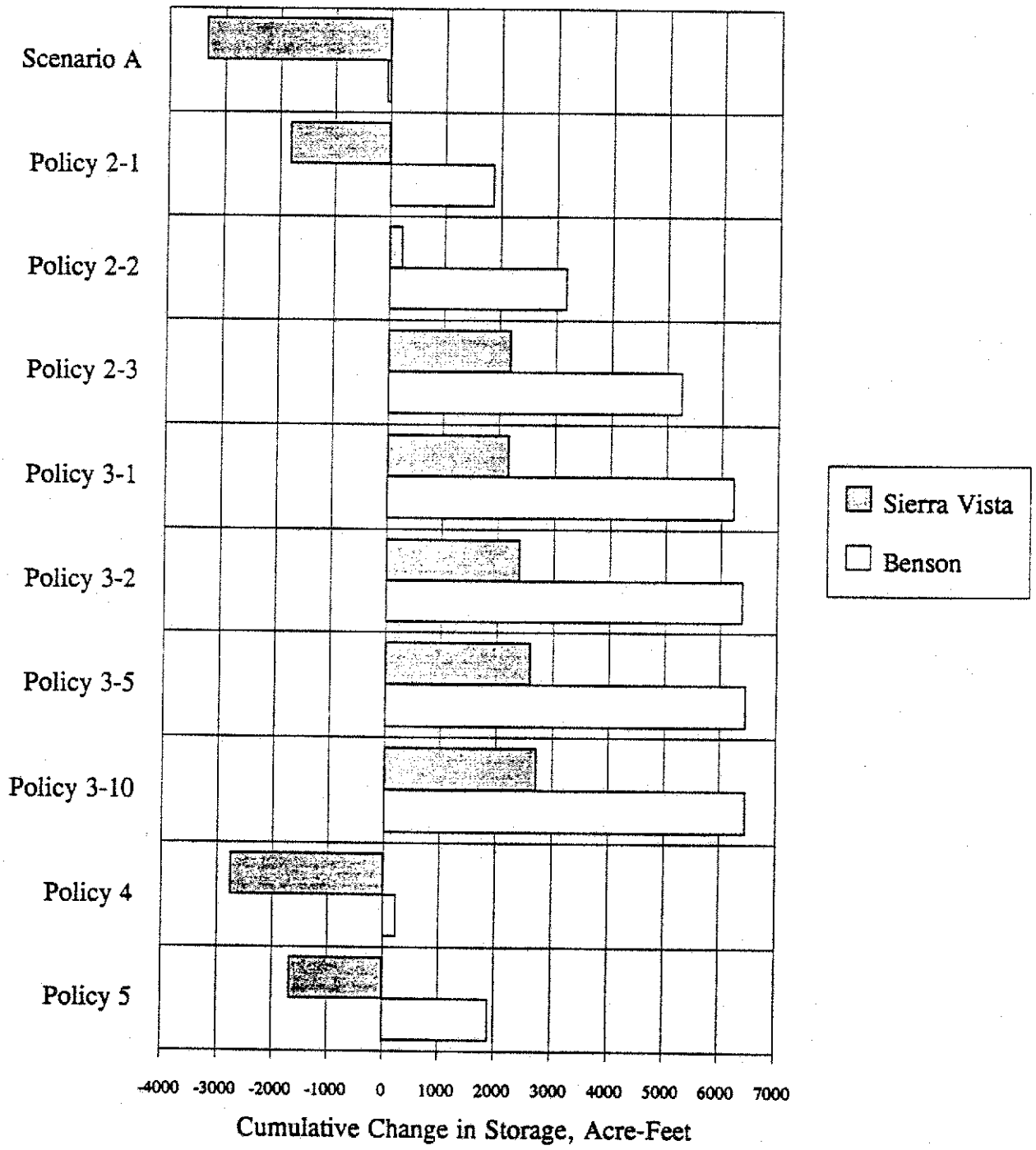


Figure 11

Cumulative Change in Floodplain Aquifer Storage After 20 Years
Under Different Policies and Scenario D Conditions, by Sub-basin

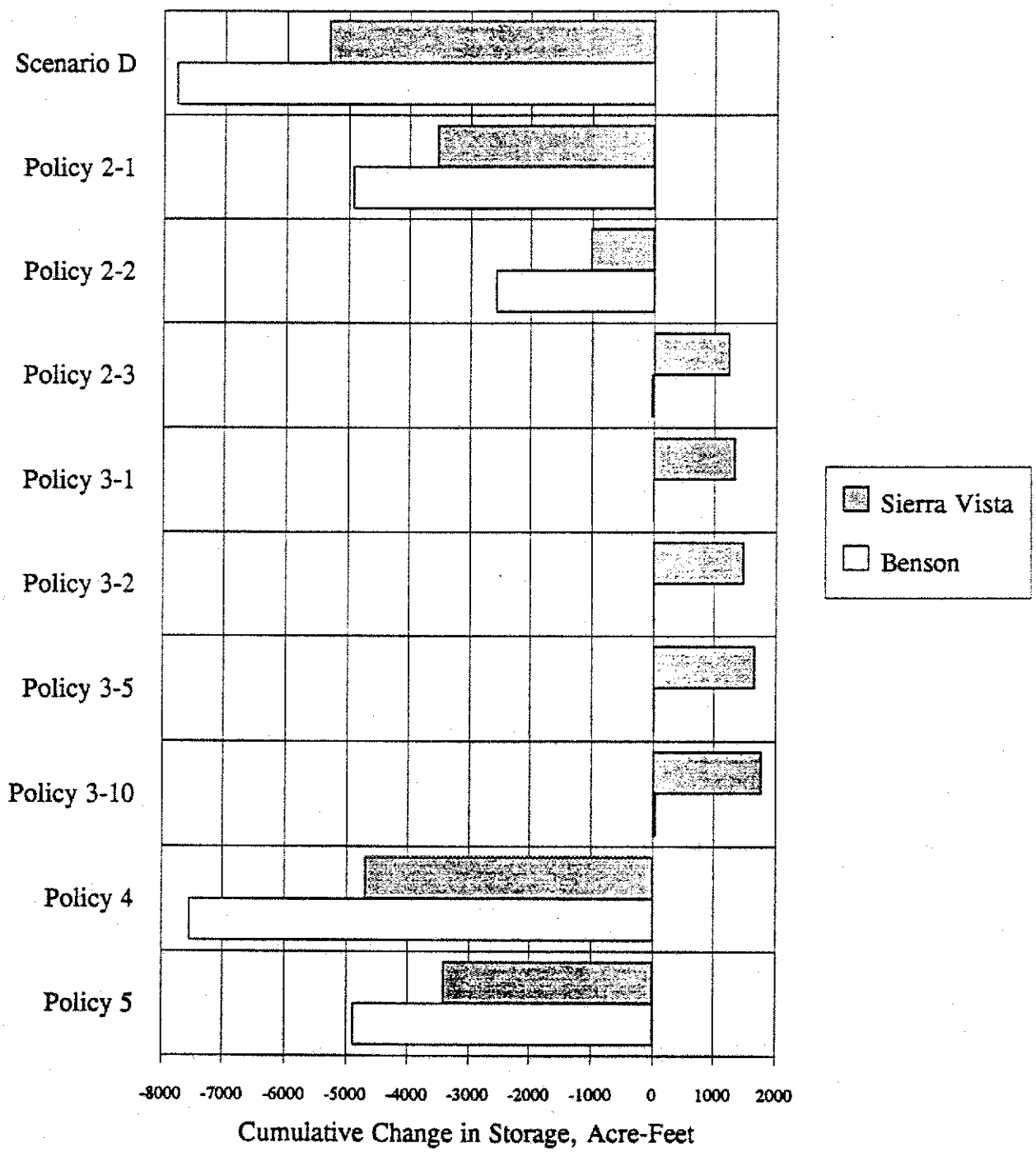


Figure 12

Cumulative Change in Regional Aquifer Storage After 20 Years
Under Different Policies and Scenario A Conditions, by Sub-basin

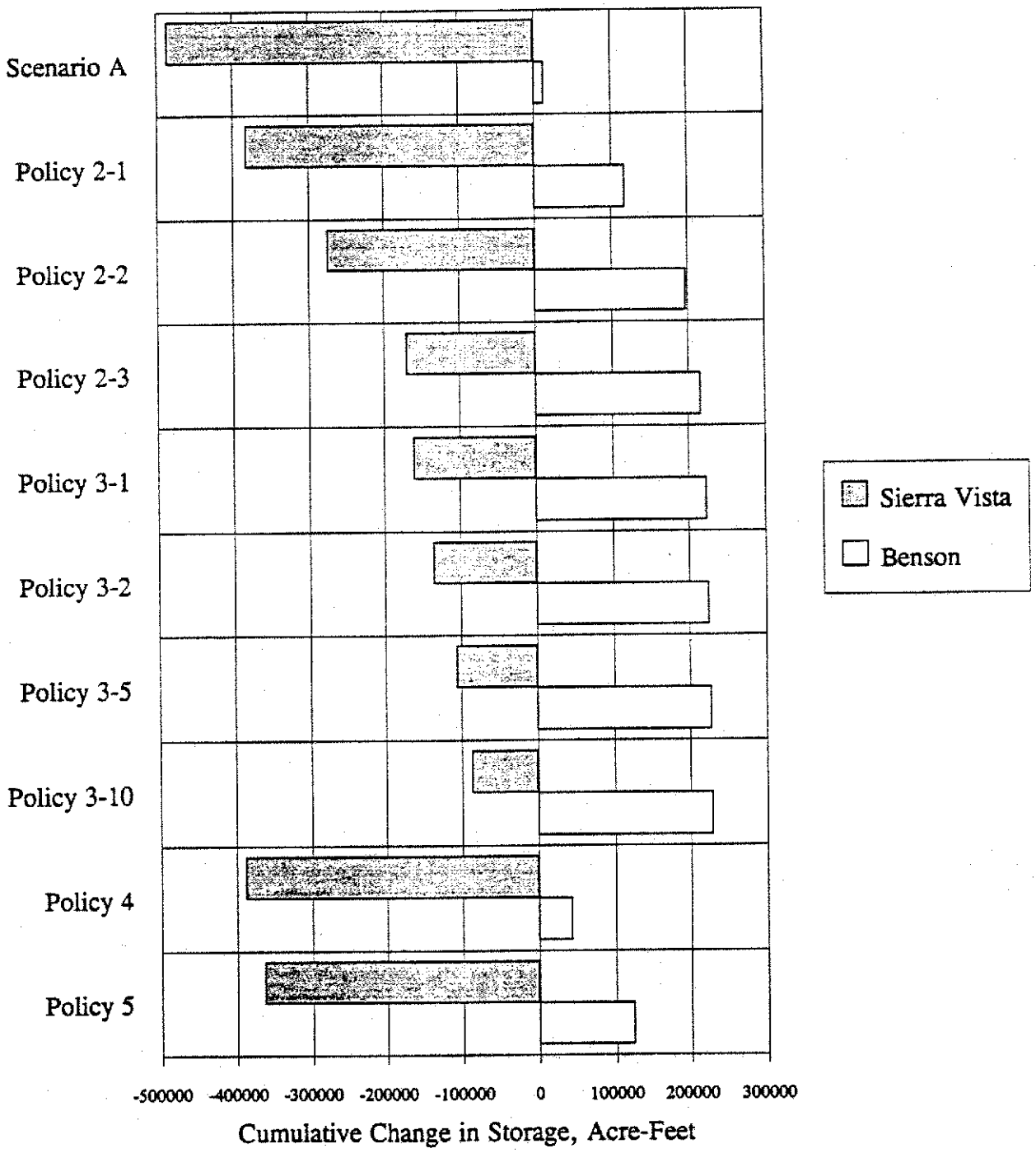


Figure 13

Cumulative Change in Regional Aquifer Storage After 20 Years
Under Different Policies and Scenario D Conditions, by Sub-basin

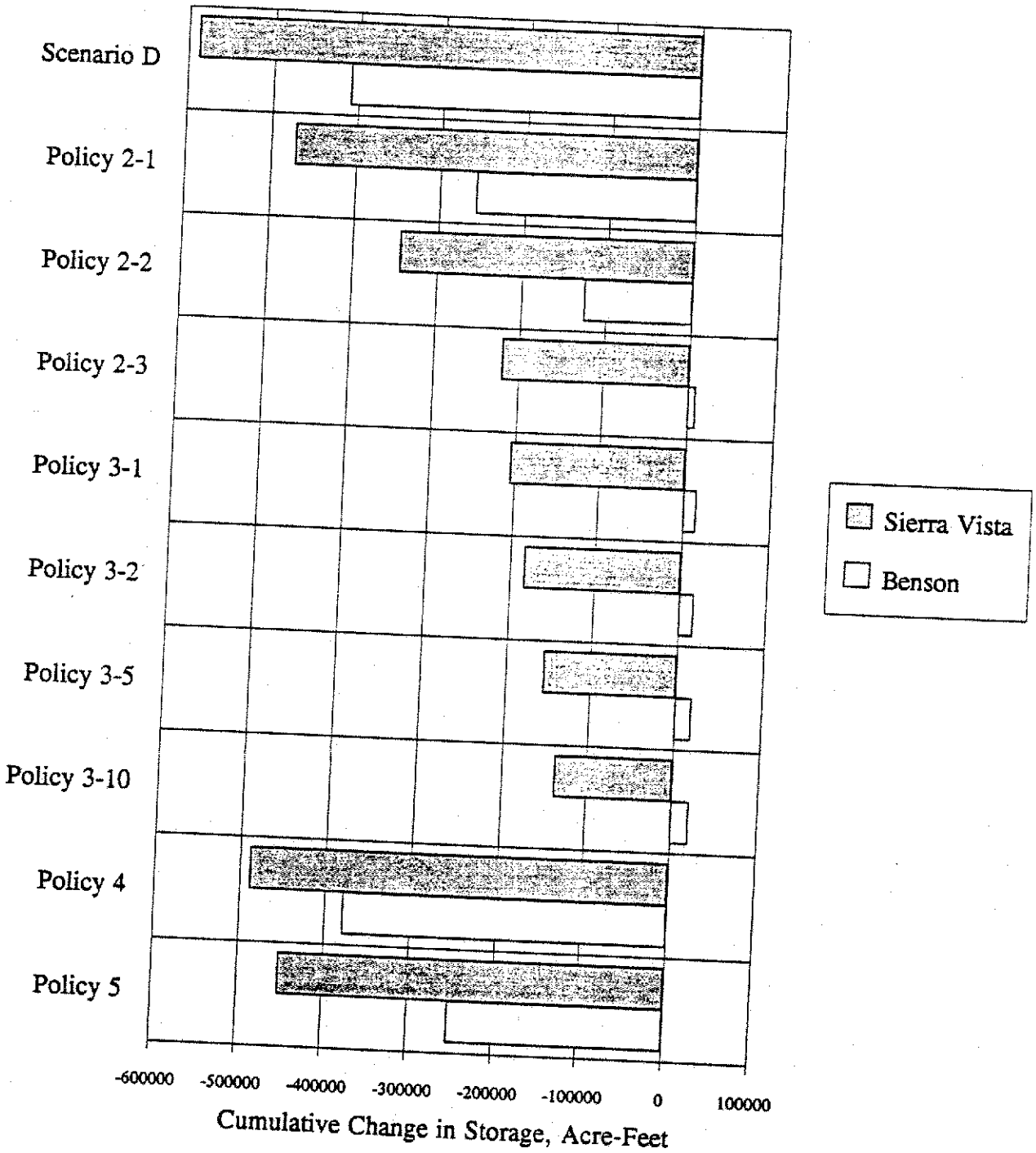


Figure 14

Annual Discharge of San Pedro River After 20 Years
Under Different Policies and Scenario A Conditions, by Sub-basin

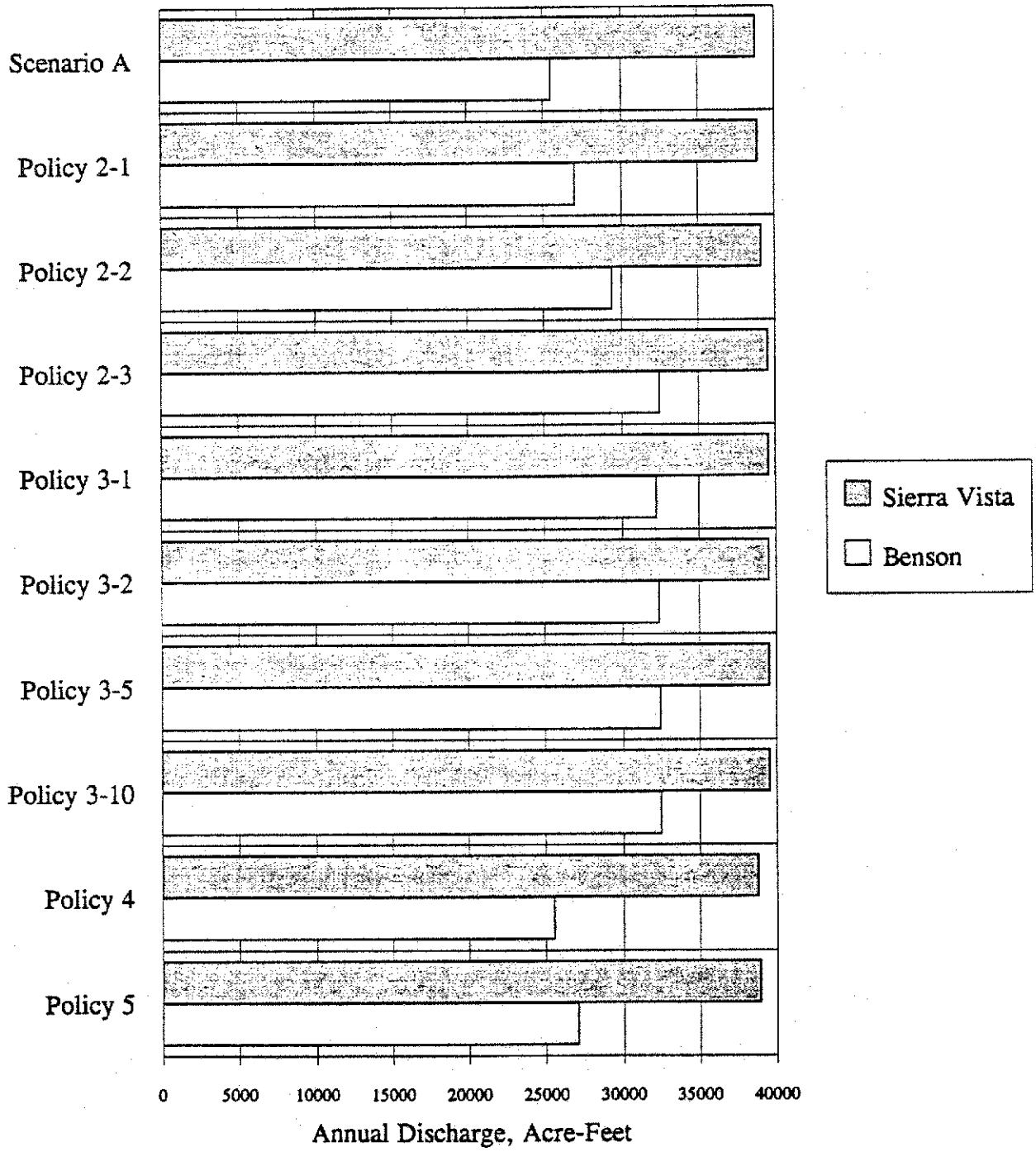


Figure 15

Annual Discharge of San Pedro River After 20 Years
Under Different Policies and Scenario D Conditions, by Sub-basin

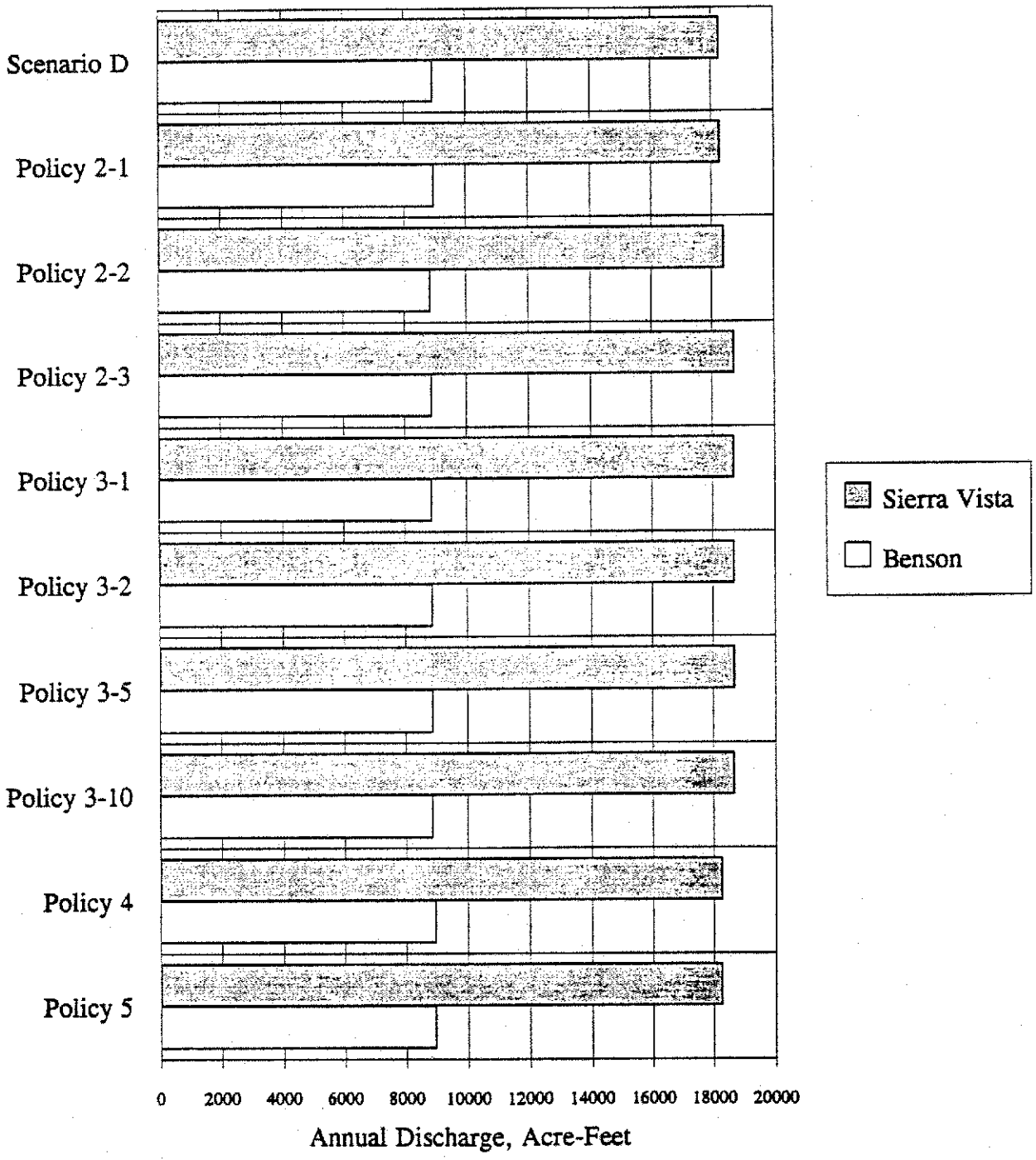


Figure 16

Cumulative Change in Area of Riparian Vegetation After 20 Years
Under Different Policies and Scenario A Conditions, by Sub-basin

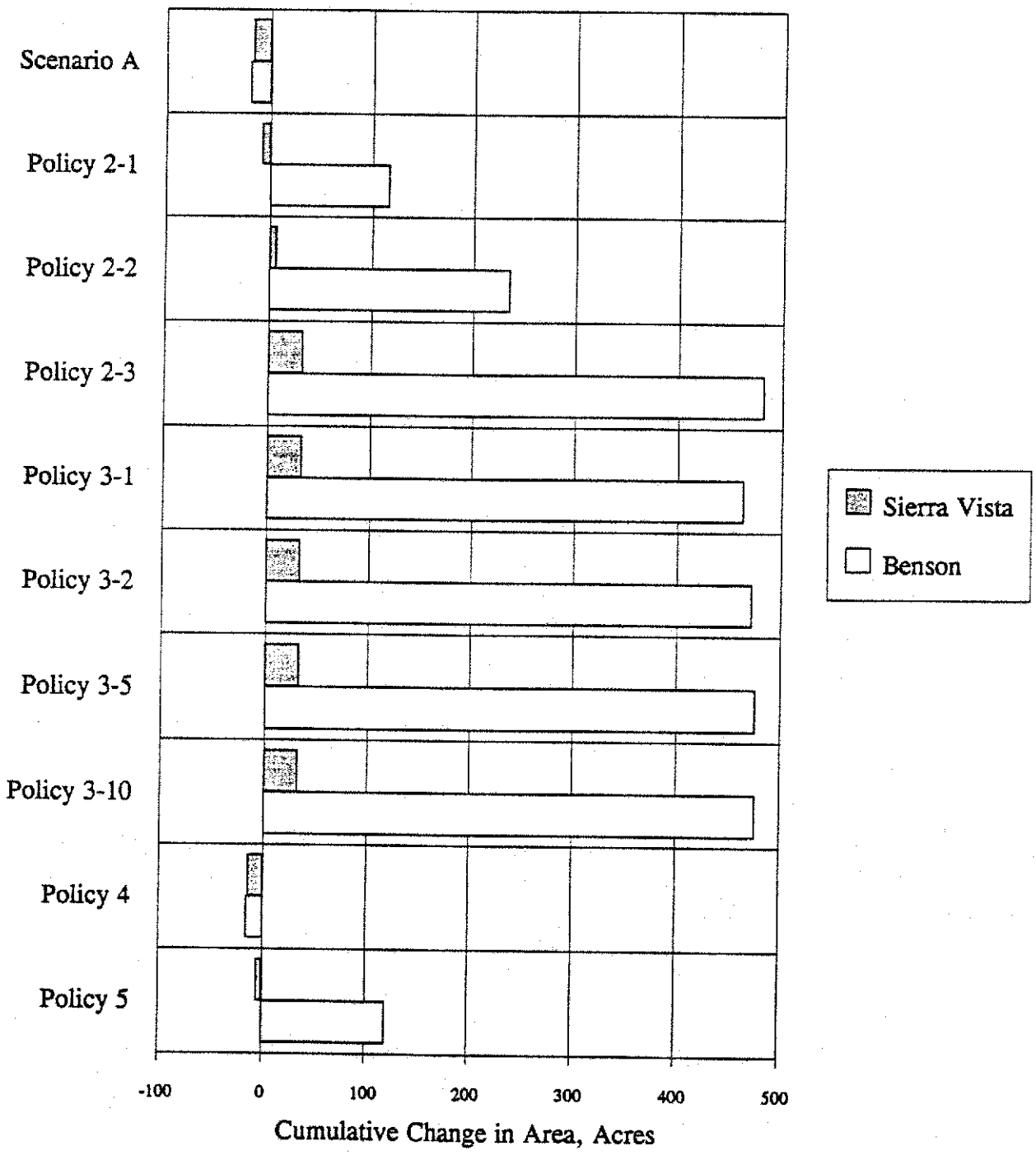


Figure 17

Cumulative Change in Area of Riparian Vegetation After 20 Years
Under Different Policies and Scenario D Conditions, by Sub-basin

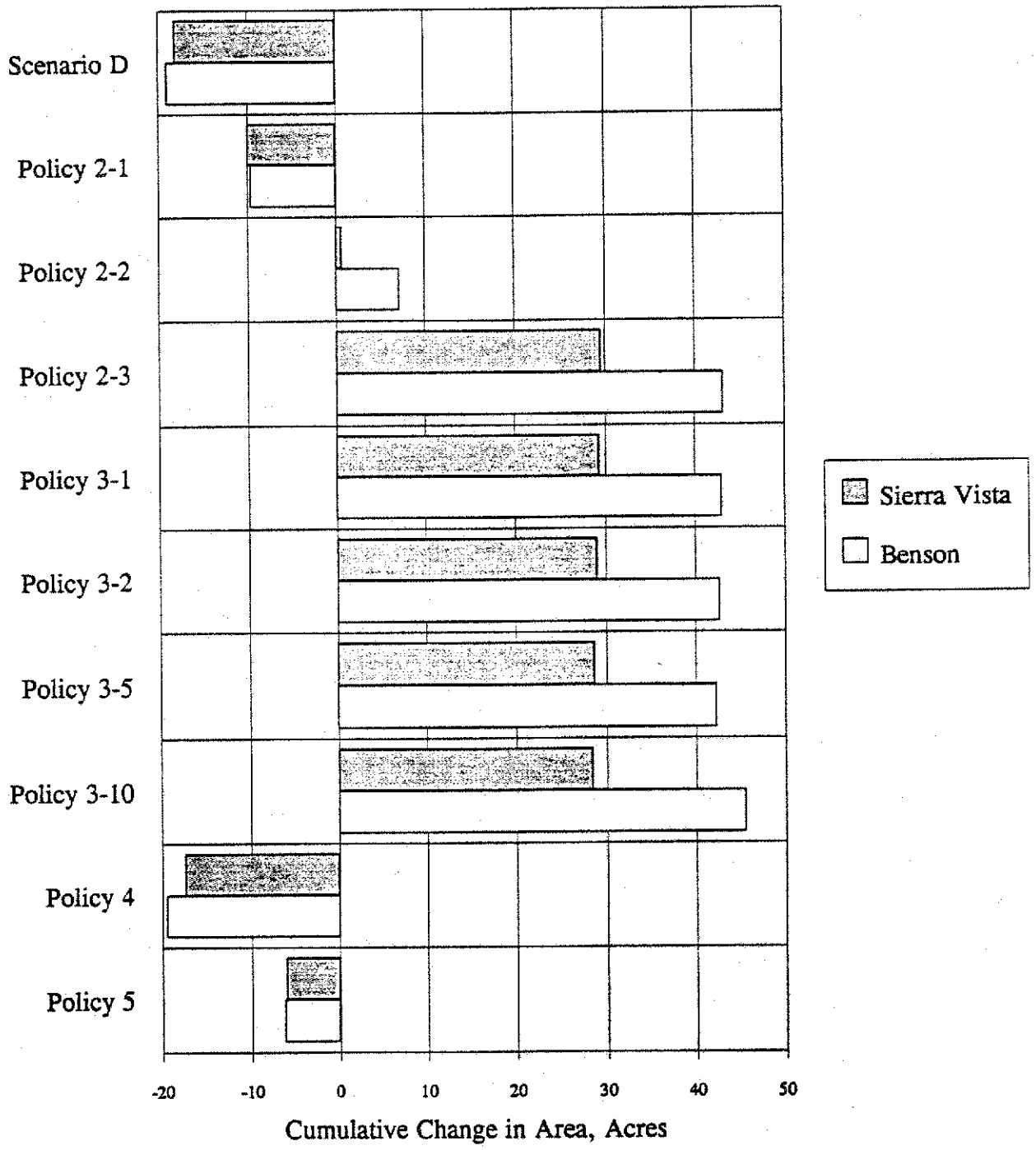


Figure 18

Cumulative Change in Irrigated Acreage After 20 Years
Under Different Policies and Scenario A Conditions, by Sub-basin

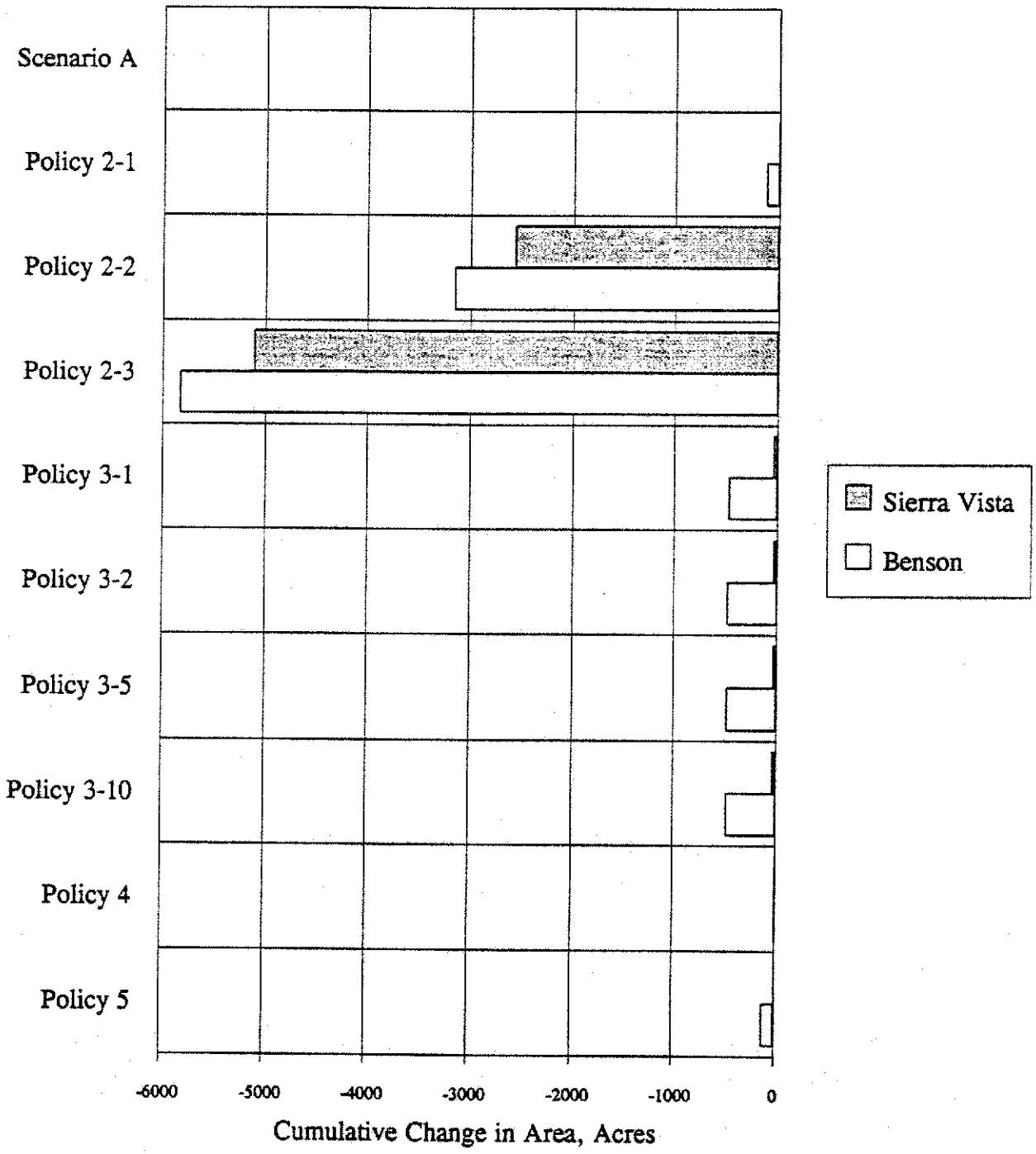


Figure 19

Cumulative Change in Irrigated Acreage After 20 Years
Under Different Policies and Scenario D Conditions, by Sub-basin

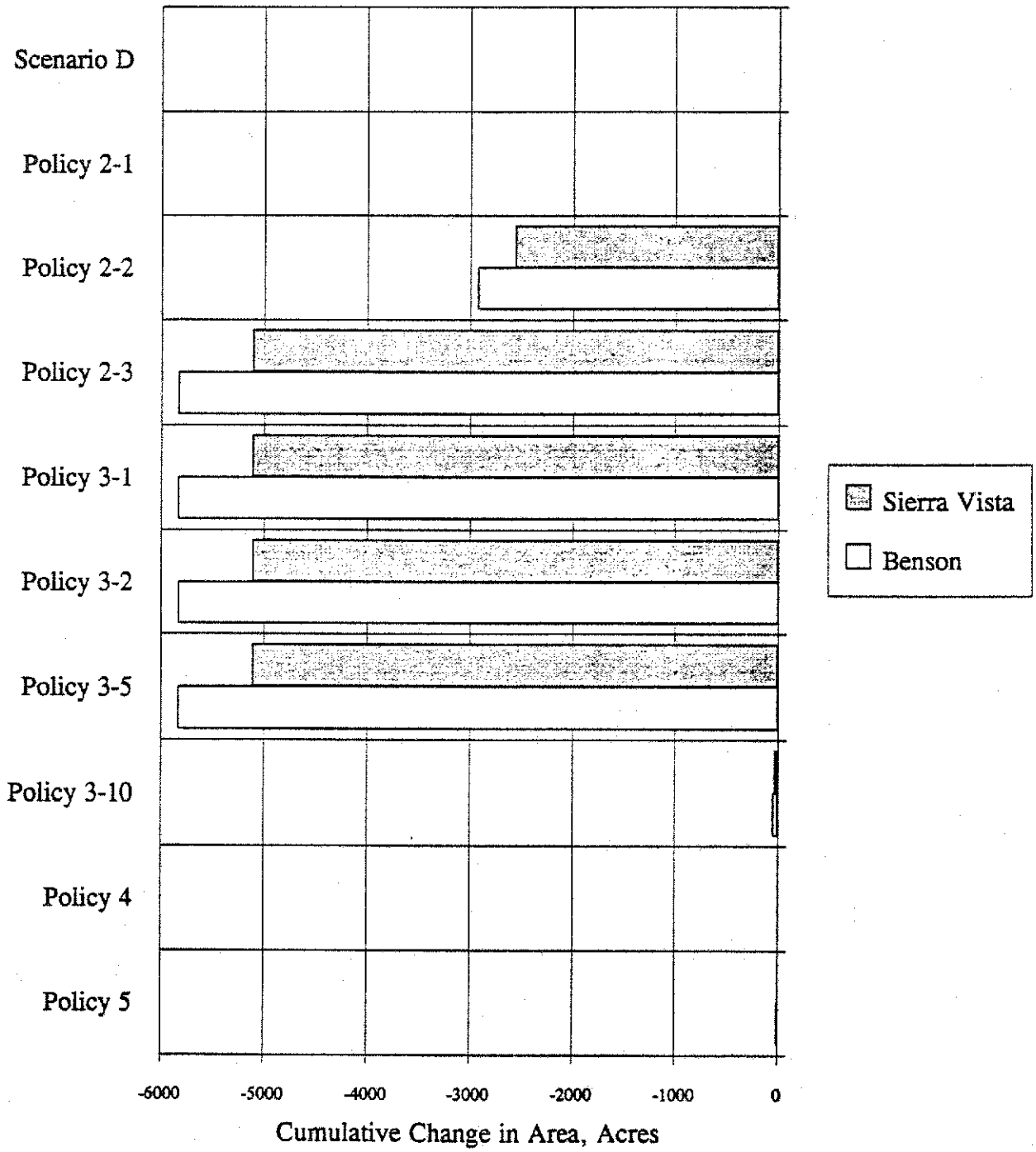
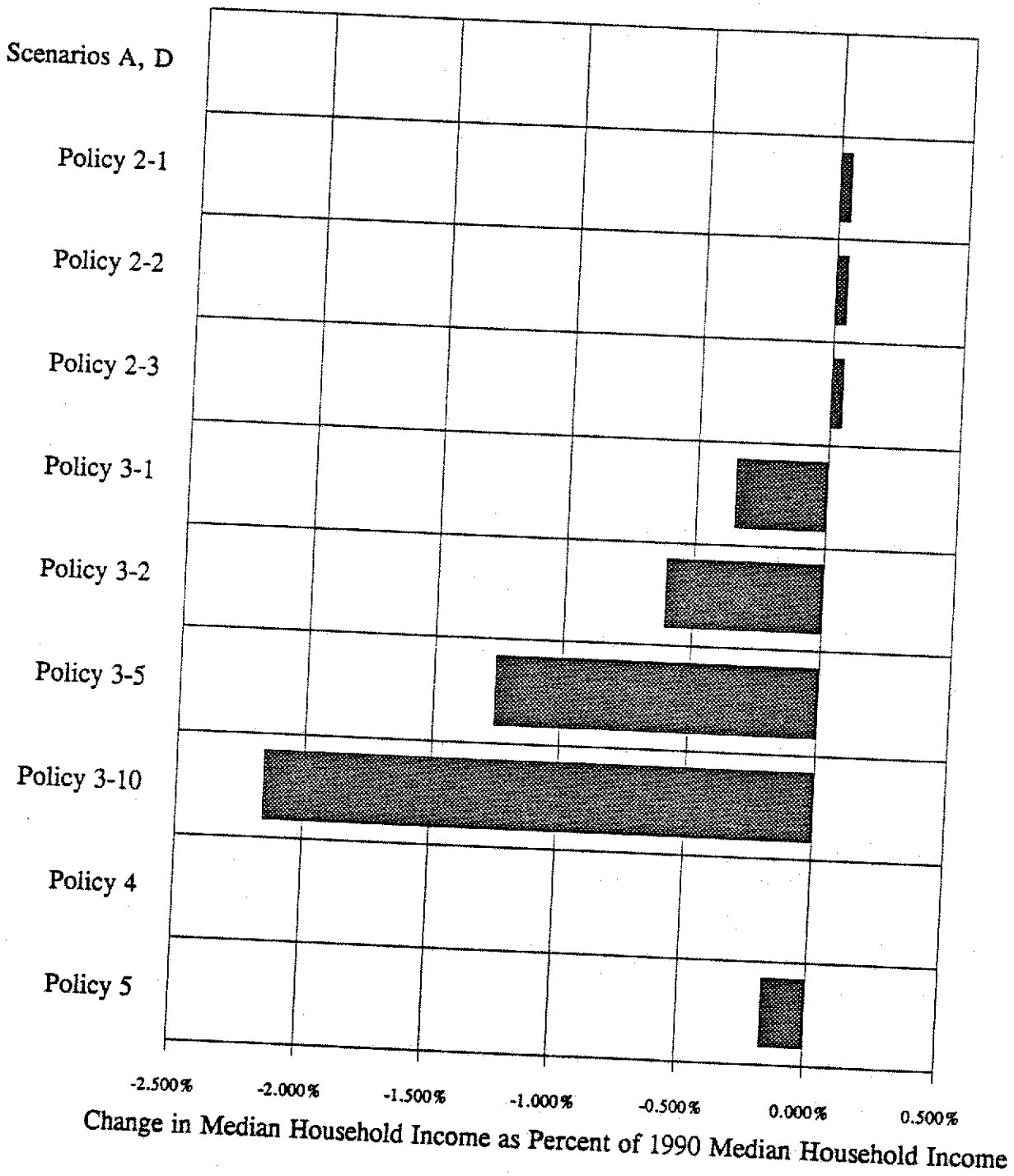


Figure 20

Change in Median Household Income Under Different Policies
Under Both Normal and Drought Conditions



MODSIM

Introduction

A computer network optimization model, known as MODSIM, was the other model developed as a management tool for evaluating water management alternatives. MODSIM was originally designed by Colorado State University. However, with the assistance of the University of Arizona, the current version has been modified to more accurately simulate the hydrologic conditions of the Upper San Pedro River Basin. The model has the capability to incorporate information about the hydrologic conditions and also institutional aspects, such as information about possible water management entities, to evaluate the water management alternatives identified by the study team. MODSIM performs a network flow simulation of water flow, storage, and consumptive use for a river basin.

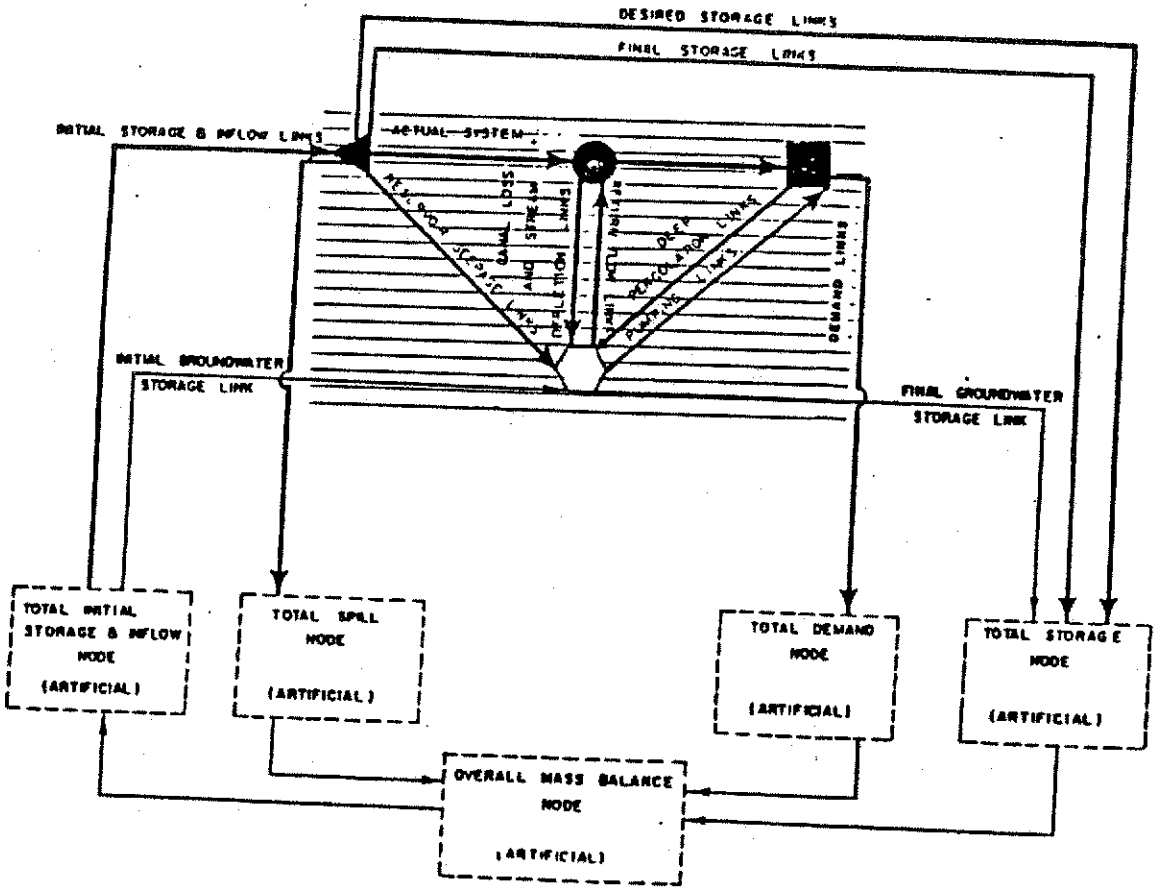
The primary assumption of MODSIM is that physical water resources systems can be represented by a fully circulating, capacitated network that is composed of nodes and links (Figure 21). Aquifers and surface resevoirs (if any) are represented as storage reservoirs, while demand locations, river confluences, points of unregulated inflow, and diversion points are represented as storage nodes. Links represent river reaches, pipelines, and canals. Multiple aquifers can be modeled and are represented in the network as groundwater reservoir storage nodes and related links. The MODSIM user is only responsible for creating the links and nodes of the actual system.

MODSIM now has an enhanced capability of modeling stream-aquifer interactions. River depletion and accretion effects are now carried over from period to period for the entire length of the study, not just within one year. These effects are calculated using ground-water coefficients for return flow from groundwater recharge events such as infiltration from irrigation, stream depletion from groundwater pumping, and return flows due to canal and river/stream seepage.

Much of the data for the model was provided by the Hydrographic Survey Report (HSR) of the San Pedro River Basin, which the Arizona Department of Water Resources (ADWR) completed for the Gila River Adjudication. Additional hydrologic information was obtained from the USGS MODFLOW model developed for use in this study, USGS streamgaging data, and other publications addressing the basin's hydrology. Economic data, including municipal and domestic water demand information, were developed by the university team.

Figure 21

Network Configuration



For MODSIM, the values for the hydrologic scenario were derived upon basin precipitation and USGS stream gaging data from 1967-1976. This 10 year hydrologic data set was run "back-to-back" for the 20 year study. It represents a somewhat drier than normal period. For example, mean annual flow at the Palominas streamgage for the 10 year period (cfs) was 27.5% below what the ADWR estimates as the mean inflow from Mexico. Also, tributary runoff within the Upper San Pedro River basin, generated from precipitation data (rate), was 21.1% below what the ADWR estimates as the amount of runoff that contributes to stream flow of the San Pedro River. Use of the dry period gives an idea of how the system performs under stress. Also, this 10 year period was selected for use in calibrating the model because the is the only period where the Benson and Tombstone USGS gages were in operation along with the Charleston and Palominas USGS stream gages.

MODSIM was used to analyze the impacts of the five scenarios listed on p. . and the five policies - Policy 1: Status Quo; Policy 2: Conventional AMA; Policy 3: Customized AMA; Policy 4: Supply Enhancement; Policy 5: Demand Management. MODSIM was unable to model the impacts of the pump tax required by Policy 3, but did examine the impacts of the retirement of agriculture on hydrologic conditions. These policies were evaluated under Scenario A, the Status Quo, and under Scenario D, Drought.

Table 6 at the end of this section presents the results of the MODSIM analysis for each of the five scenarios and for the policies to be able to compare the results with WATERBUD. The MODSIM results are described below.

Scenarios

The model was run for the twenty year time period for all five scenarios. The overdraft of the basin was confirmed. Figure 22 shows the twenty year cumulative change in the regional aquifer storage for both sub-basins under the five scenarios. The average annual loss in storage ranged from about 15,500 af/yr for Scenario A to about 24,200 af/yr for Scenario B. Figure 23 shows the cumulative loss in storage over time for the Sierra Vista sub-basin regional aquifer. Scenarios C,D, and E have about an equal impact.

Figure 22

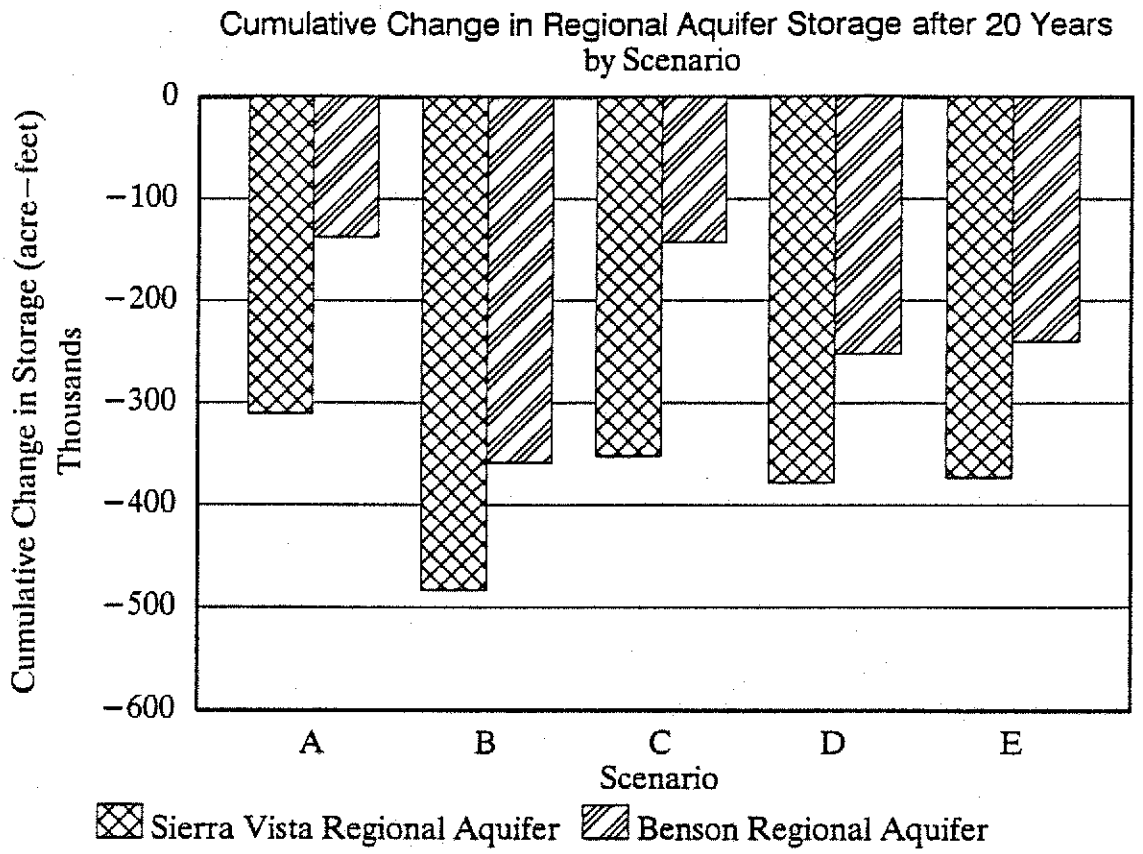

Cumulative Change in Regional Aquifer Storage after 20 Years
by Scenario
Cumulative Change in Storage (acre−feet)
Thousands
0
−100
−200
−300
−400
−500
−600
A
B
C
D
E
Scenario
Sierra Vista Regional Aquifer
Benson Regional Aquifer

Figure 23

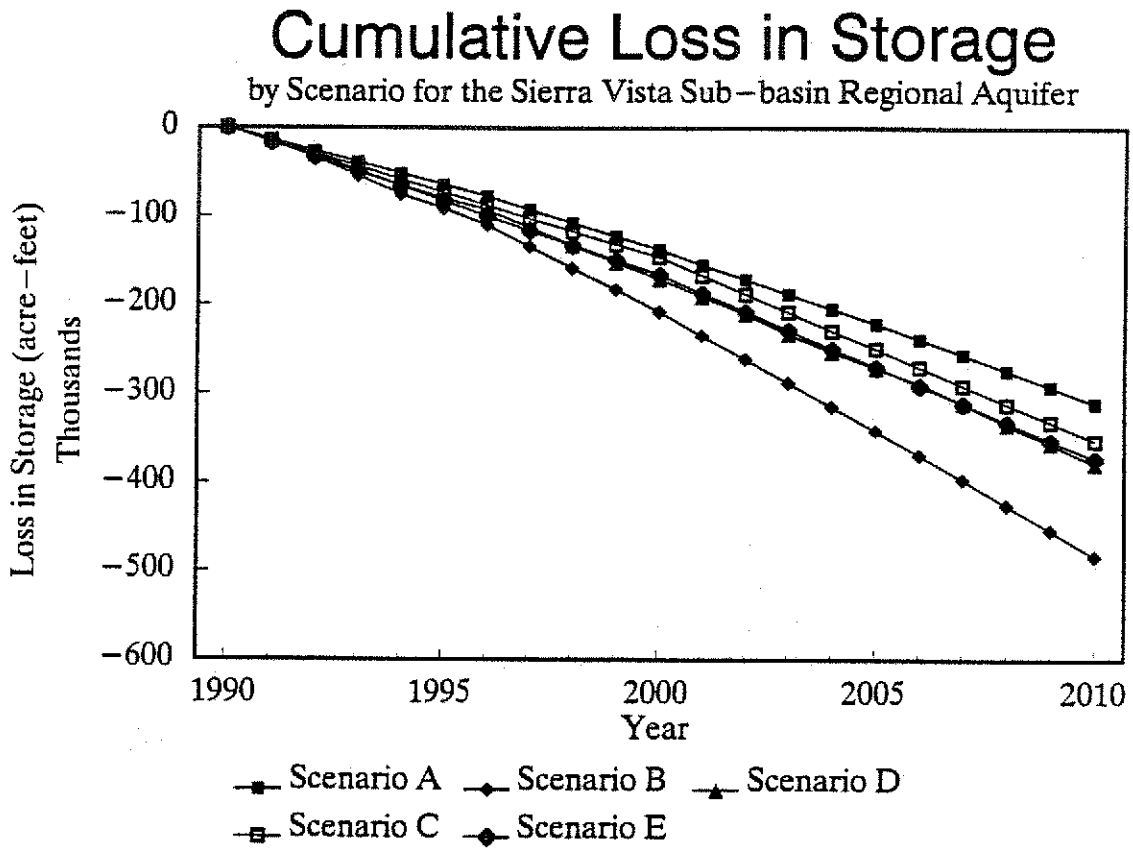

Cumulative Loss in Storage
by Scenario for the Sierra Vista Sub−basin Regional Aquifer
Loss in Storage (acre−feet)
Thousands
0
−100
−200
−300
−400
−500
−600
1990
1995
2000
2005
2010
Year
Scenario A
Scenario B
Scenario D
Scenario C
Scenario E

Figure 24 shows the resulting cumulative change in the floodplain aquifer storage for each scenario. Only the results for scenarios B and E, which feature increasing pumping for irrigation use, demonstrated any negative impact on the floodplain aquifer. Because the negative impact is nearly the same for scenarios B and E, and because there is no impact for scenarios C and D, it can be concluded that the increase in irrigation pumping is responsible for the loss of storage in Scenario B. The impact is significant because nearly 50% of the storage in the floodplain aquifer is lost after 20 years.

Figure 25 shows the monthly storage in the floodplain aquifer for the Sierra Vista sub-basin during the twenty year run. It appears that pumping from the 3.5% annual growth rate in irrigated agriculture exceeded the floodplain aquifer's ability to recharge itself from the regional aquifer, and to a lesser extent, the San Pedro River. The threshold occurs during the sixth year of the run.

Figure 26 demonstrates how pumping in the regional aquifer for the Sierra Vista sub-basin draws water from the floodplain aquifer. Annual values ranged from about 7,000 af to 18,000 af. However, this amount is less than the amount of groundwater pulled out of the regional aquifer by pumping in the floodplain aquifer. The flux from the regional to the floodplain aquifer, not including natural recharge, ranged from about 21,000 to 31,000 af/yr. Although the results indicate groundwater pumping in the Sierra Vista area does not have significant impact on the floodplain aquifer and riparian system. In other words, the 20 year study is not long enough to show the true impacts of the regional groundwater pumping on the floodplain aquifer and the river system.

Figure 27 show the reduction in San Pedro stream flow due to increasing irrigation pumping in the Sierra Vista sub-basin, while Figure 28 shows river depletion under conditions of no growth in irrigated agriculture. The peaks on the graphs represent the spring and summer season of heavy irrigation pumping, while the valley represent the winter and fall seasons of low irrigation activity.

Figure 29 indicates the percentage of seasonal streamflow lost as a result of pumping in the floodplain aquifer. For each season, there is a general increase in the overall trend in river depletion due to increasing irrigation withdrawals. Streamflow reductions was studied under Scenario B to measure the impacts of growth and a drought to see if it was possible to pump the river dry. However, the greatest impact during any season was about a 75% reduction.

Figure 24

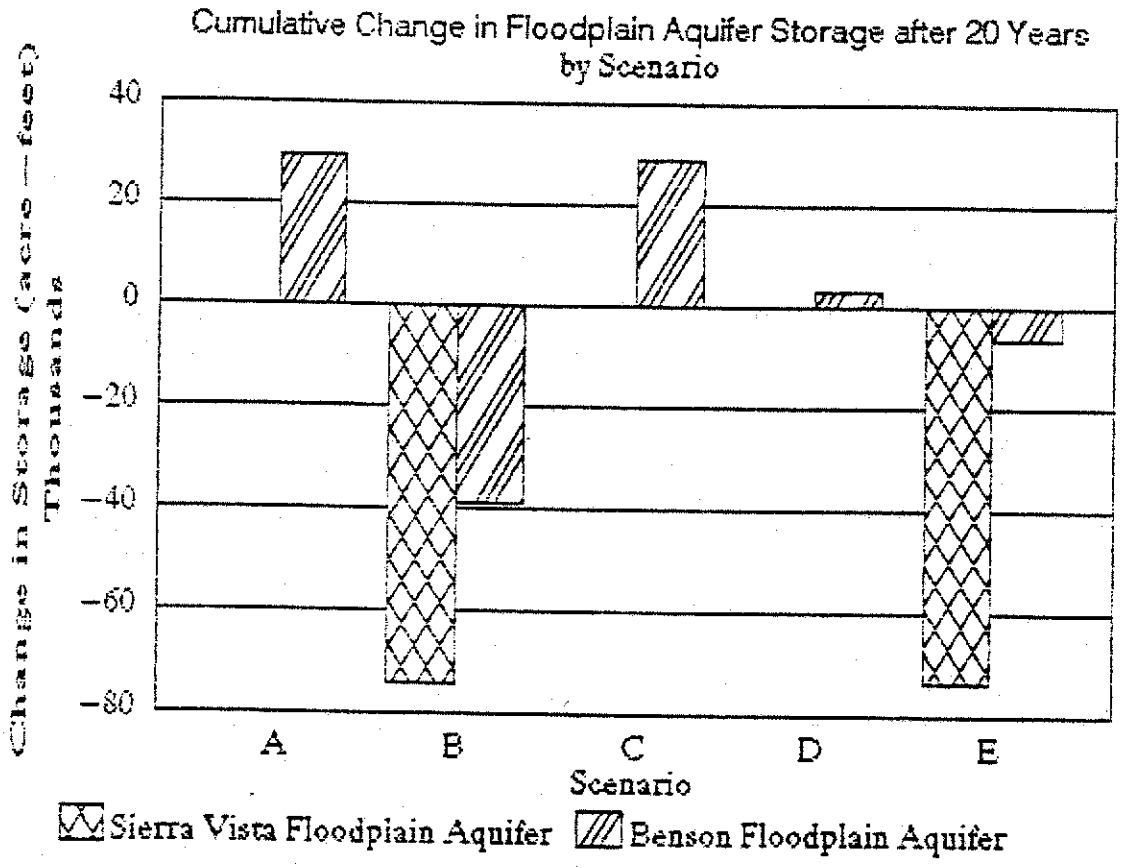

Cumulative Change in Floodplain Aquifer Storage after 20 Years
by Scenario
Change in Storage (acre — feet)
Thousands
40
20
0
−20
−40
−60
−80
A
B
C
D
E
Scenario
Sierra Vista Floodplain Aquifer
Benson Floodplain Aquifer

Figure 25

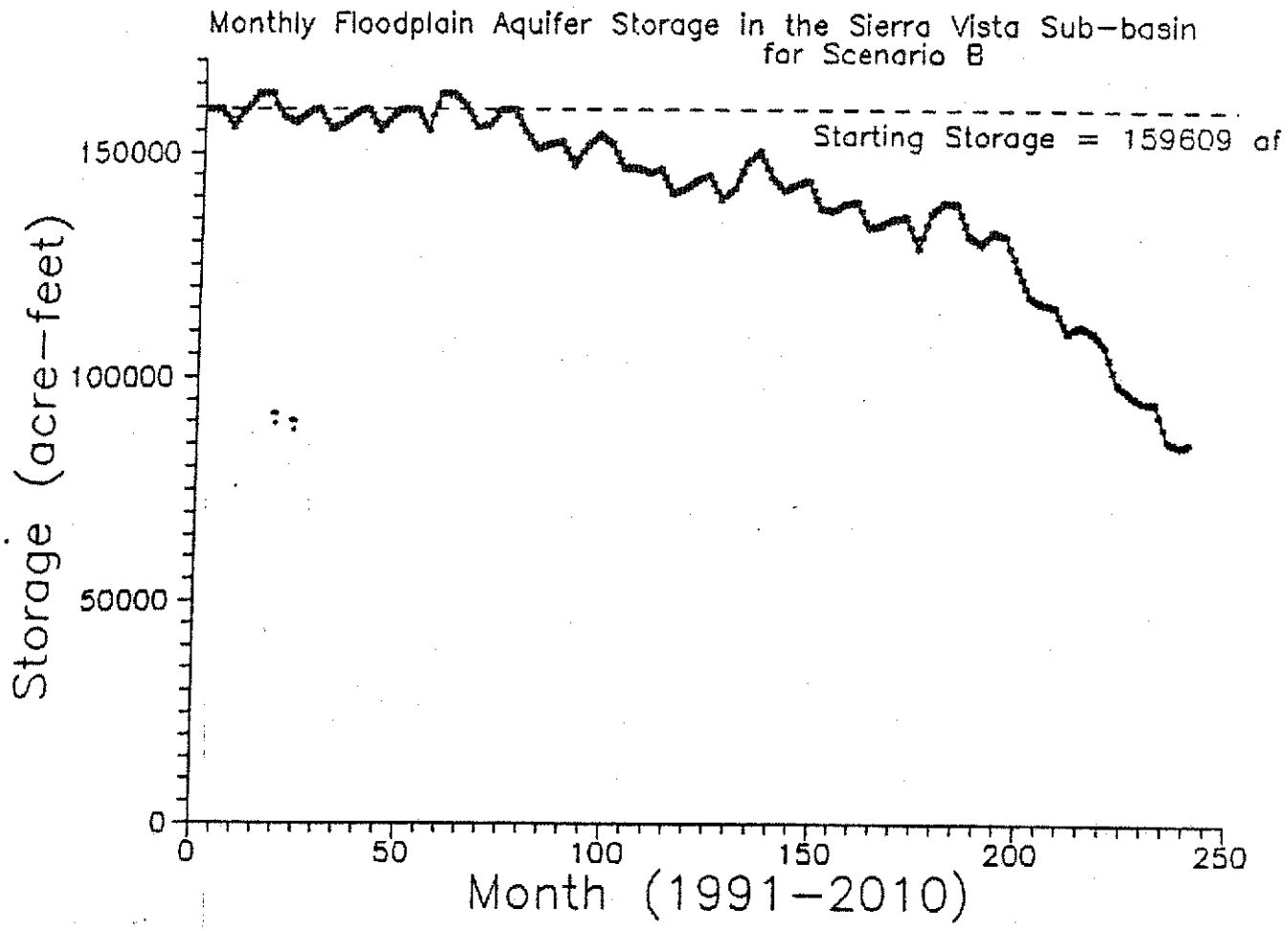

Monthly Floodplain Aquifer Storage in the Sierra Vista Sub-basin
for Scenario B
Starting Storage = 159609 af
150000
100000
50000
0
Storage (acre-feet)
0
50
100
150
200
250
Month (1991-2010)

Figure 26

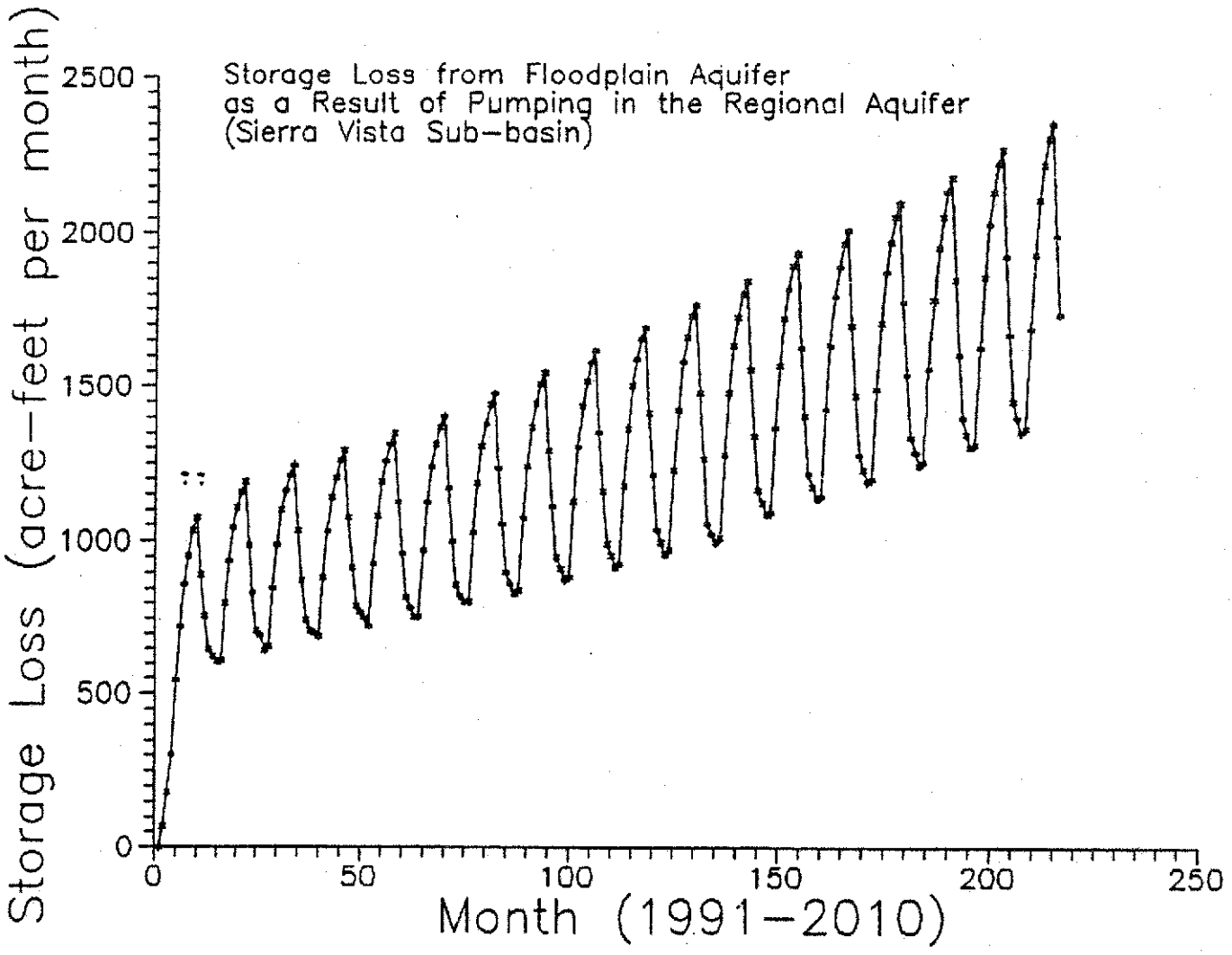

Storage Loss from Floodplain Aquifer
as a Result of Pumping in the Regional Aquifer
(Sierra Vista Sub-basin)
Storage Loss (acre-feet per month)
2500
2000
1500
1000
500
0
0
50
100
150
200
250
Month (1991-2010)

Figure 27

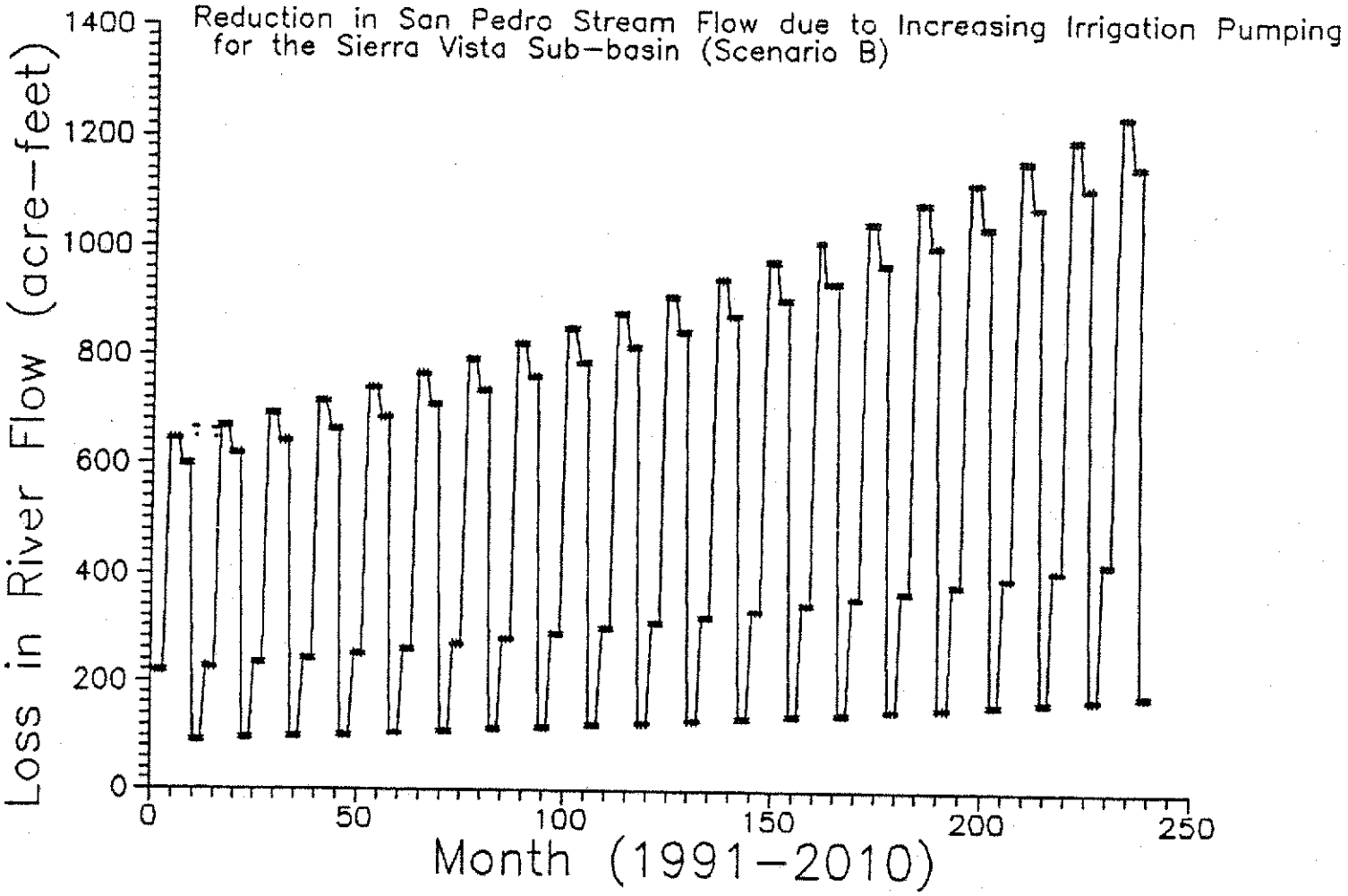

Reduction in San Pedro Stream Flow due to Increasing Irrigation Pumping
for the Sierra Vista Sub-basin (Scenario B)
Loss in River Flow (acre-feet)
1400
1200
1000
800
600
400
200
0
0
50
100
150
200
250
Month (1991-2010)

Figure 28

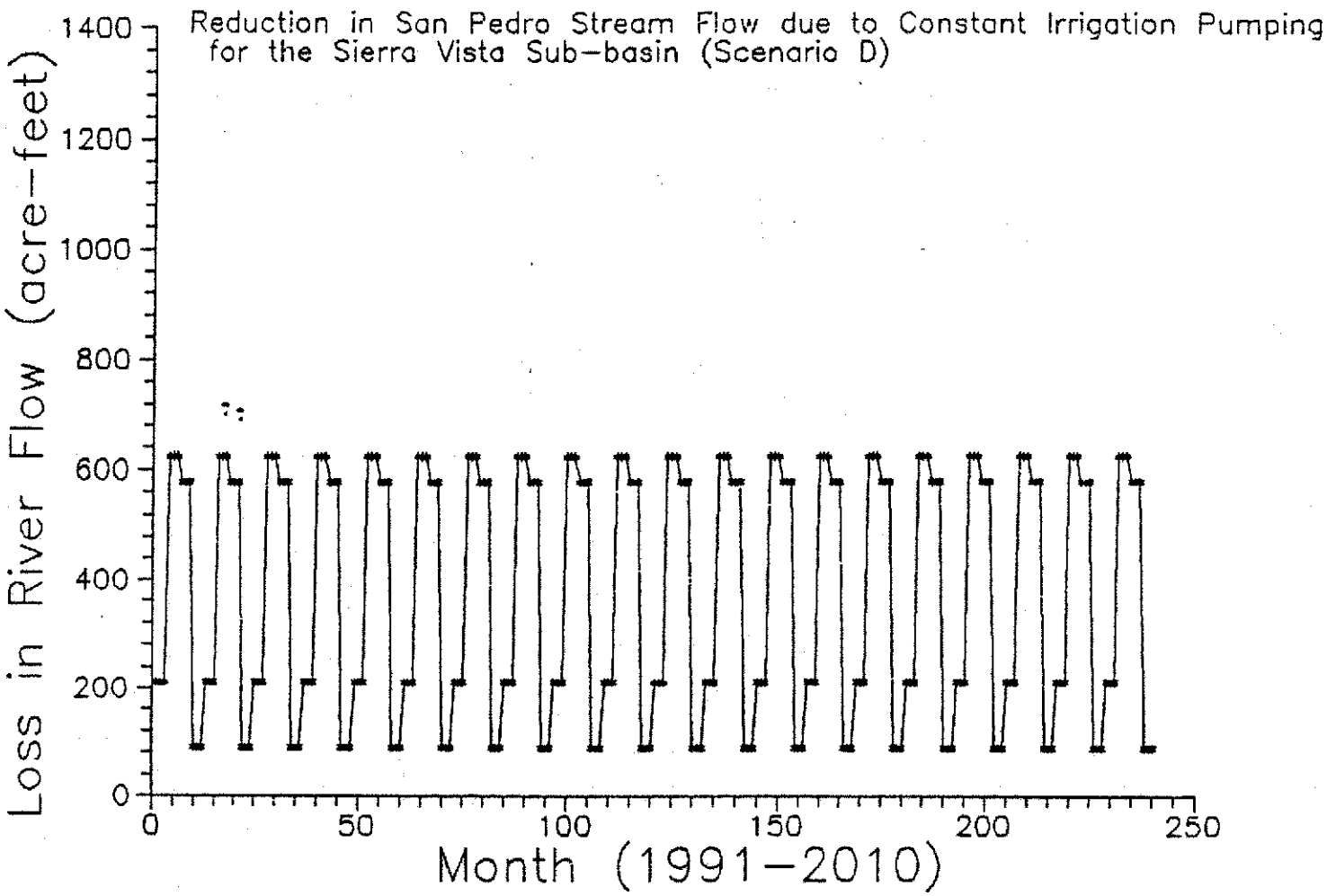

Reduction in San Pedro Stream Flow due to Constant Irrigation Pumping
for the Sierra Vista Sub-basin (Scenario D)
Loss in River Flow (acre-feet)
1400
1200
1000
800
600
400
200
0
0
50
100
150
200
250
Month (1991-2010)

Figure 29

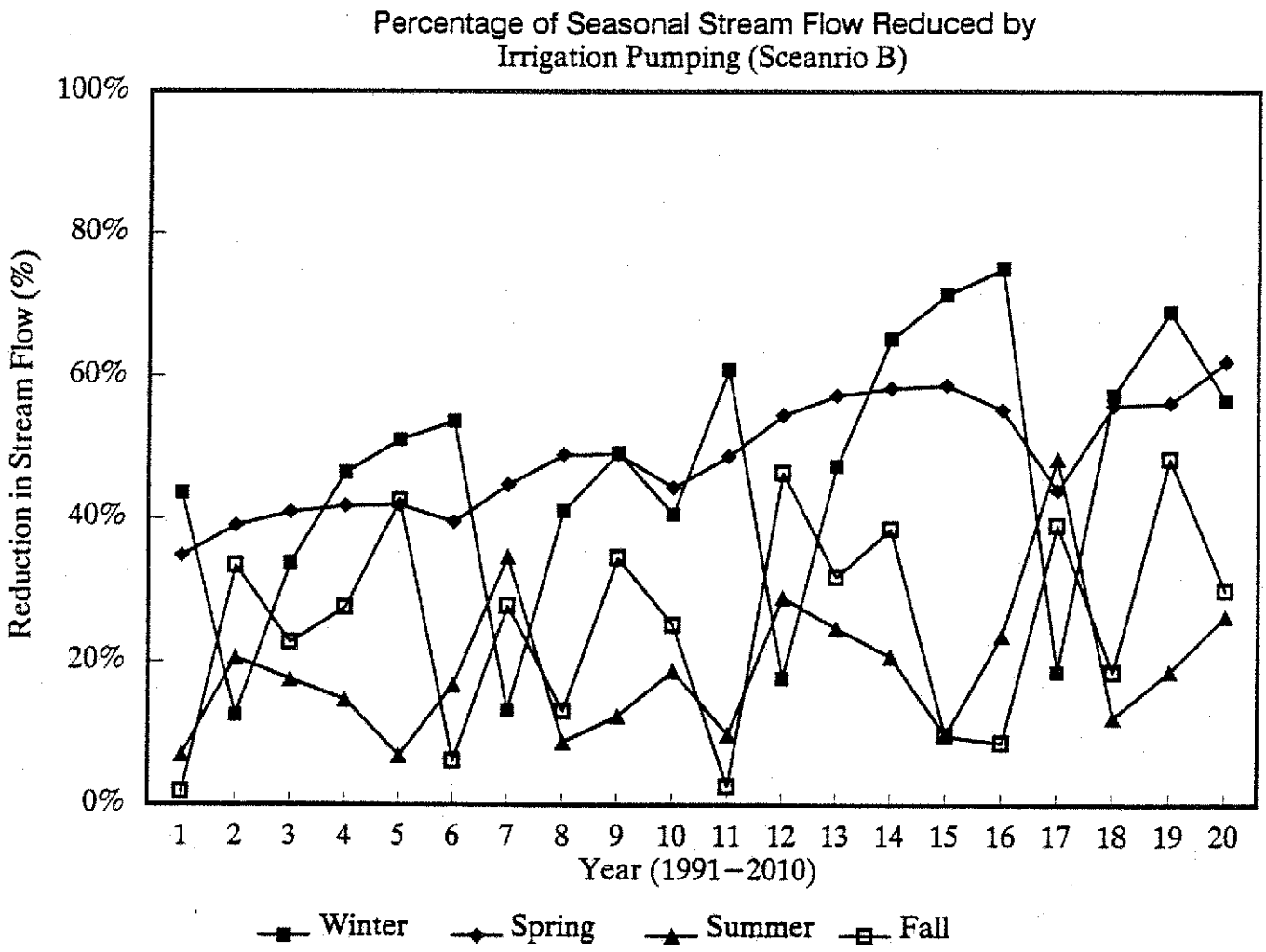

Percentage of Seasonal Stream Flow Reduced by
Irrigation Pumping (Sceanrio B)
100%
80%
60%
40%
20%
0%
Reduction in Stream Flow (%)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Year (1991–2010)
Winter
Spring
Summer
Fall

Figure 30 and 31 show how results for stream flow under the worst case (high ag and drought) compare with BLM minimum stream flow requirements. Figure 30 show that there are some periods when the instream flow requirement is not met and Figure 31 shows minimum flows may not be met in the Winter season. These results indicate that the riparian system is not threatened with extinction within 20 years. However the system could be stressed severely in the near future if conditions of drought and increasing pumping from the floodplain aquifer, especially during the low flow seasons. The longer-term effects of groundwater pumping at current levels, to say nothing of possible increased levels, could be expected to be more serious.

Policy Options

All management alternatives show they will reduce the rate at which the groundwater supplies are being depleted, but will not bring the basin to safe-yield. Figures 32 and 33 show how the management alternatives improve upon the cumulative change in storage in the regional aquifer for the scenarios A and D, but do not eliminate the overdraft situation.

An AMA which eliminates irrigated agriculture altogether, is most effective in remedying the problem of groundwater depletion. Under normal conditions (Scenario A), this type of AMA approximately attains safe-yield conditions for the entire basin because the deficit in the Sierra Vista area is offset by a surplus in Benson sub-basin.

Of the remaining alternatives, Demand Management is just slightly better than the conventional AMA and Supply Enhancement in reducing cumulative loss in storage for the Sierra Vista sub-basin regional aquifer. Supply Enhancement has very little effect in the Benson sub-basin regional aquifer because of the small quantities of treated effluent available for recharge. In addition, this policy does not control demand, and therefore, pumpage.

In the case of streamflow, the four management alternatives also show varying degrees of improvement in stream flow over the status quo. Again, the management alternatives which reduced irrigation consumption increased stream flow most effectively. The complete elimination of irrigated agriculture in the "No-ag" AMA alternative resulted in the highest average seasonal streamflows. The Conventional AMA and Demand Management alternatives ranked second in their ability to improve stream flow conditions over the status quo. Supply Enhancement results showed only marginal improvements.

Figure 30

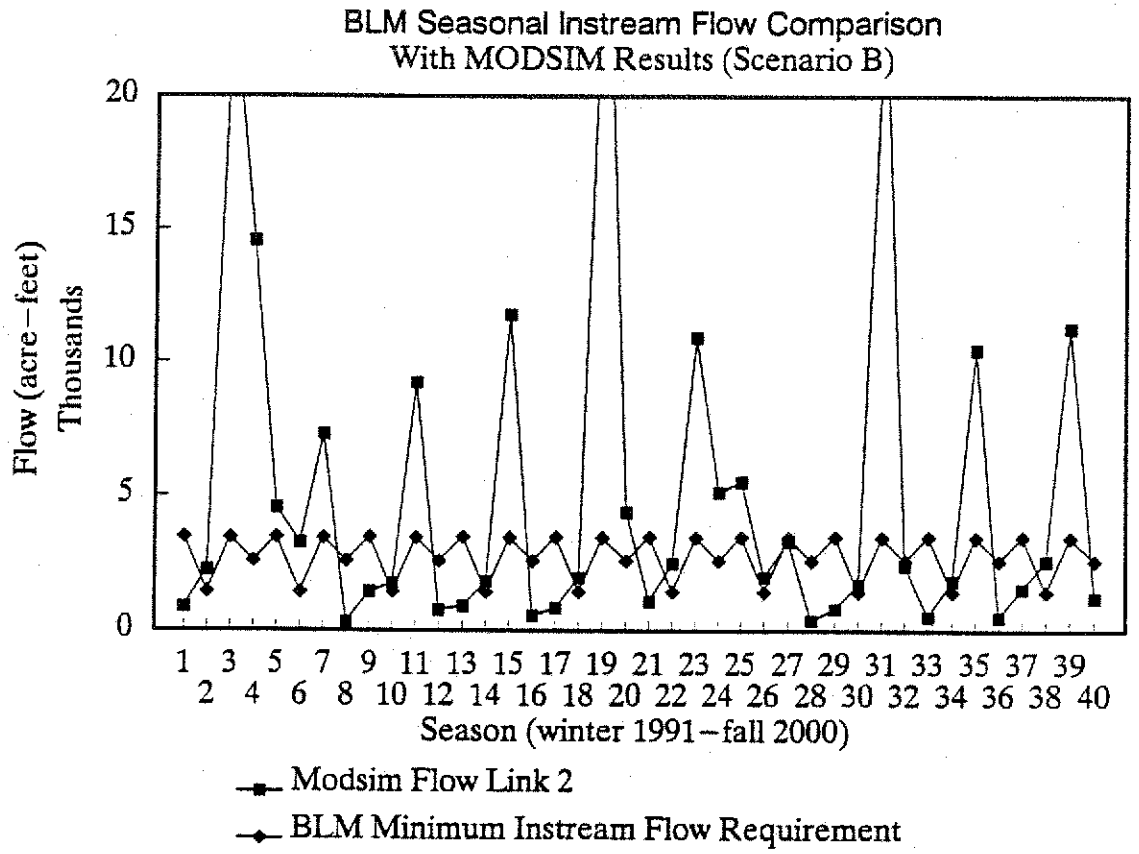

BLM Seasonal Instream Flow Comparison
With MODSIM Results (Scenario B)
Flow (acre–feet)
Thousands
20
15
10
5
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
Season (winter 1991–fall 2000)
Modsim Flow Link 2
BLM Minimum Instream Flow Requirement

Figure 31

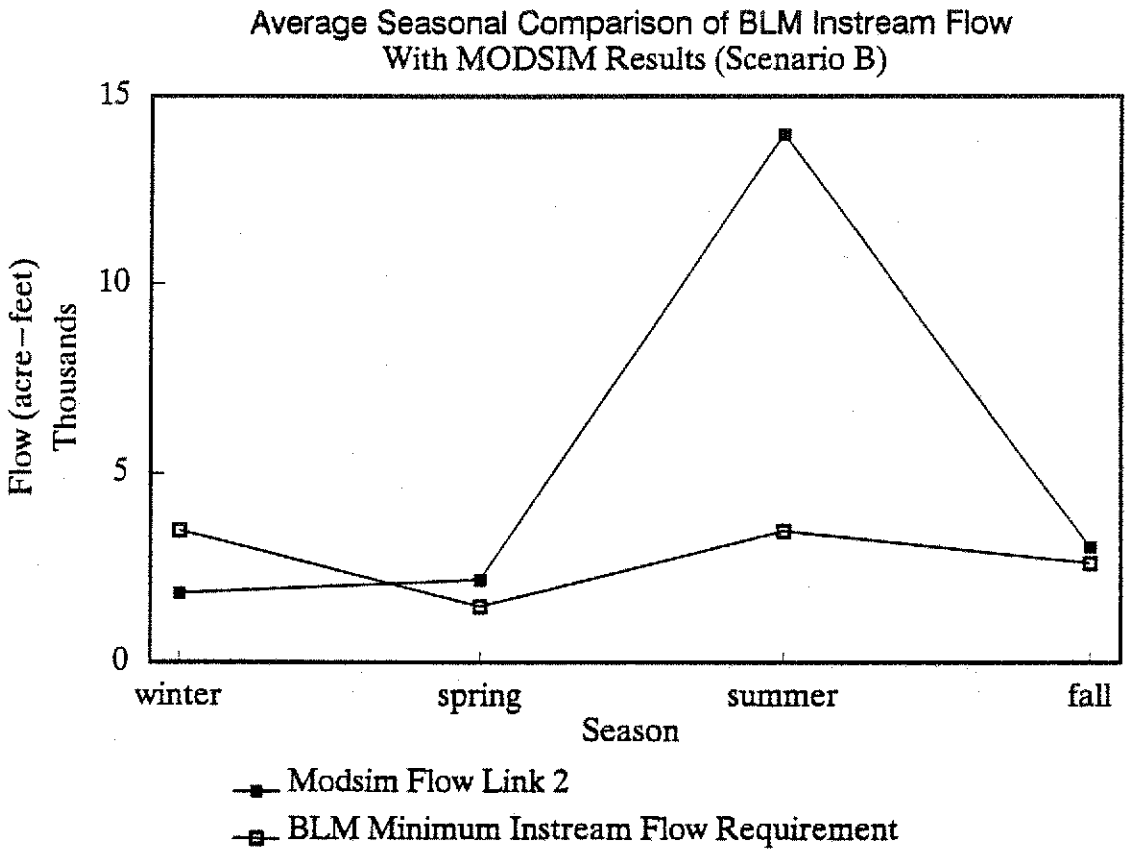

Average Seasonal Comparison of BLM Instream Flow
With MODSIM Results (Scenario B)
15
10
5
0
Flow (acre-feet)
Thousands
winter
spring
summer
fall
Season
Modsim Flow Link 2
BLM Minimum Instream Flow Requirement

Figure 32

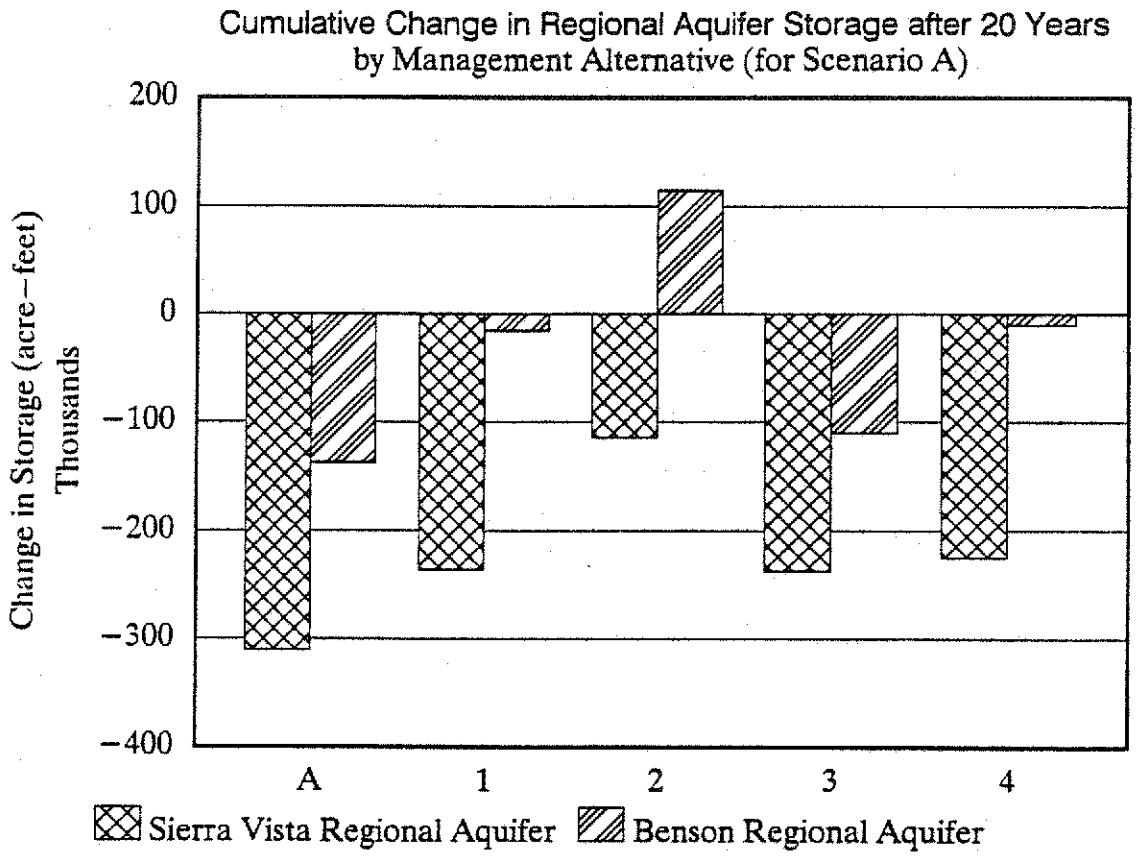
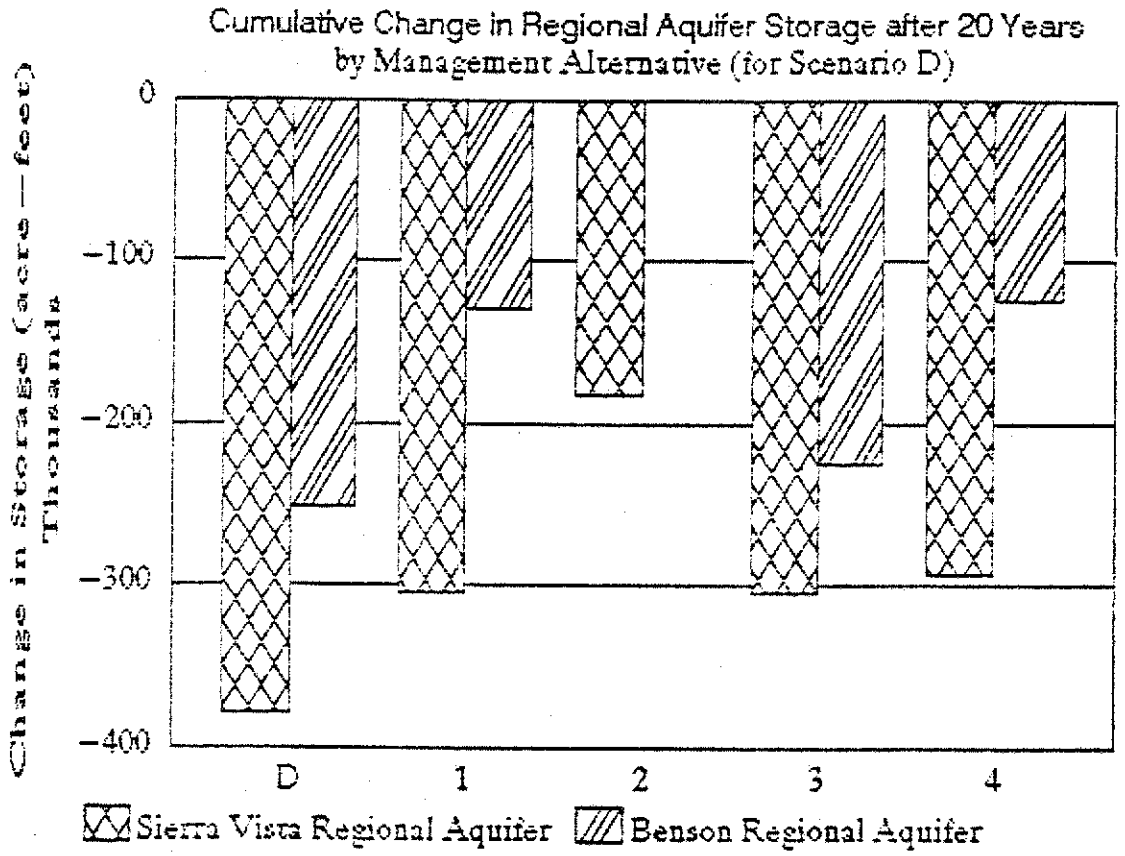

Cumulative Change in Regional Aquifer Storage after 20 Years
by Management Alternative (for Scenario A)
Change in Storage (acre–feet)
Thousands
200
100
0
−100
−200
−300
−400
A
1
2
3
4
Sierra Vista Regional Aquifer
Benson Regional Aquifer

Figure 33


Cumulative Change in Regional Aquifer Storage after 20 Years
by Management Alternative (for Scenario D)
Change in Storage (acre — feet)
Thousands
0
−100
−200
−300
−400
D
1
2
3
4
Sierra Vista Regional Aquifer
Benson Regional Aquifer

However, the fact that there are actually some improvements in stream flow suggests that management activities for the regional aquifer demands do impact the inner valley. It illustrates the inter-connectivity of the regional aquifer, floodplain aquifer, and riparian systems. Nonetheless, the small magnitude of the impacts indicates the 20 year study period is not long enough to determine how regional aquifer pumping and recharge will effect both the floodplain aquifer and the San Pedro river.

Conclusion

Results show substantial interaction between all elements of the basin. The floodplain aquifer is the crucial "link" in these interactions. Model results show that both the San Pedro stream flow and flow from the regional aquifer recharge the floodplain aquifer.

Irrigation pumping in the floodplain aquifer imposes the greatest and most immediate man-made stress on the system. It intensifies the overdraft situation in the regional aquifer and causes a significant storage loss in the floodplain aquifer under scenarios of increasing agricultural growth.

Table 6 presents a summary of the MODSIM results for each policy option.

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Table 6

SUMMARY OF MODSIM RESULTS

PROJECTED CUMULATIVE EFFECTS OF ALTERNATIVE POLICIES AFTER TWENTY YEARS, RELATIVE TO 1990 CONDITIONS

	Regional Aq. Sierra Vista Sub. (acre feet)	Floodplain Aq. Sierra Vista Sub. (acre feet)	San Pedro River Sierra Vista Sub. (acre-feet/year)	Regional Aq. Benson Sub. (acre feet)	Floodplain Aq. Benson Sub. (acre feet)	San Pedro River Benson Sub. (acre-feet/year)
INITIAL CONDITIONS						
1990, "Normal" Conditions	31730841	159609	39190	27065444	123681	25500
	total change	total change	average change	total change	total change	average change
TWENTY-YEAR EFFECTS OF POLICY 1						
Scenario A	-310600	206	-6229	-138030	29199	751
Scenario B	-483268	-73902	-19460	-359163	-38798	-3175
Scenario C	-352484	0	-6229	-142860	29078	751
Scenario D	-378602	0	-18180	-252368	3250	-2062
Scenario E	-373176	-73696	-7999	-239995	-6470	-2062
TWENTY-YEAR EFFECTS OF POLICY 2						
Policy 2-1, Scenario A	-236701	206	-5124	-15345	27675	3418
Policy 2-1, Scenario D	-304703	0	-17075	-129683	1726	605
Policy 2-3, Scenario A	-114500	206	-2508	114338	30581	8637
Policy 2-3, Scenario D	-182502	0	-14459	0	4632	5823
TWENTY-YEAR EFFECTS OF POLICY 4						
Scenario A	-237394	206	-6099	-110314	29287	834
Scenario D	-305396	0	-18050	-224652	3338	-1980
TWENTY-YEAR EFFECTS OF POLICY 5						
Scenario A	-225181	206	-3562	-9772	27790	3418
Scenario D	-293183	0	-15513	-124110	1841	605

MULTI-ATTRIBUTE TRADEOFF SYSTEM (MATS)

Introduction

This portion of the study concerns exploring future water management options for the San Pedro River Basin. One of the first steps in water resources planning is the identification of appropriate water management objectives. These objectives are multi-dimensional, due to the existence of multiple water interests in the basin, and to the complex value systems which characterize basin residents. Formulating appropriate water management objectives under such circumstances is always difficult. For example, there is a strong commitment among basin residents to preserve the existing perennial flow within the San Pedro Riparian Conservation Area. However, development is placing increasing demands on the water supply.

The Multi-Attribute Tradeoff System, (MATS), is a computer program developed by the Bureau of Reclamation to aid in the determination of objectives. It is an analytical tool that can provide a framework for complex decision analysis. Its primary value is that it can help determine a decisionmaker's preferences or values about water policy managment options. These preferences can be used to evaluate alternatives to produce a ranking of options. In the case of the San Pedro River Basin, MATS can be used to evaluate water management alternatives using criteria derived from the underlying values of basin residents.

MATS structures a decision through the use of five components: FACTORS, FUNCTION FORMS, WEIGHTS, PLANS, and IMPACTS. FACTORS are measurable representations of the values upon which the evaluation of alternatives will be based. Numeric scales are used to quantify the factors. For example, in the San Pedro Basin, factors could include the price of water, the preservation of the agricultural segment of the local economy, and/or future economic growth.

WEIGHTS rank the FACTORS relative to one another in each decision-maker's preference function. For example, an environmentalist might attach more weight to factors such as preservation of the riparian habitat and less to a rapid rate of growth. A strong proponent of economic growth and development might reverse those emphases.

The FUNCTION FORM is an expression of how the weights attached to each of the factors vary with varying levels of provisions of the factor. Technically, it expresses the marginal utility of the factor as contrasted to the weight, which expresses its average utility.

PLANS are simply the options or alternatives that a decisionmaker may choose among. These plans are formulated outside of MATS and are specified within it solely by their impacts.

IMPACTS are the way in which a plan effects the FACTORS. The estimation of these impacts is normally a function performed by planning models. It is not a part of MATS. In this case, WATERBUD provides the necessary impact estimates. Once all these components have

been entered, an evaluation that combines the values of the decision-makers and the plans'impacts can be made. This evaluation will produce a ranking of the alternatives.

However, the quality of the MATS analysis is highly dependent on the proper definition of the components. If the FACTORS in particular are ill-defined, the analysis will be faulty. The MATS Manual lists four important questions which must be answered to properly structure the components:

1) What is the overall objective being measured?

2) What are the elements of the alternatives that contribute to the overall objective or goal?

3) How many factors should be used in the analysis?

4) What units are appropriate for each FACTOR?

Other considerations are that the list of FACTORS be complete, relevant, measurable, meaningful, and value dependent.

Identification of Participants

The study consisted of five distinct phases. The first phase involved gathering a pool of possible active participants. Every member of the San Pedro Water Management Council was asked to list at least five people who they felt were knowledgeable and/or interested in water issues in the basin. Every person's name appearing on these lists was then also asked to list at least five people they felt were knowledgeable and/or interested in basin water issues. This process continued until no new names were identified by those returning lists. This "snowball" technique yielded a total of over 150 names.

Identification of Social Values

The second phase of the study involved the identification of pertinent social values to be considered when designing future water management strategies for the basin. The challenge at this stage is twofold; all relevant social values relating to water management in the basin should be addressed, while still keeping the resulting number of factors as manageable (small) as possible. A list of possible values was generated by the university team and then circulated to all of the over 150 persons identified through the use of the snowball technique.

For the study, four social values were chosen. The first, Economic Well-Being, is defined as the economic prosperity and viability of the basin community and its members. The second, Amenity/Environmental Quality, refers to the quality of life aspects such as the

condition of the environment and other aesthetic concerns. The third social value is Autonomy. This refers to how much control basin residents have over water management decisions. The fourth is Distribution of Economic Impacts/Equity, which addresses the perceived fairness in the distribution of water supply benefits and costs. This value concerns how these costs and benefits are distributed.

Selection of Factors

Once the relevant social values have been identified, a way to measure them had to be found. In the language of the MATS program, these measures are called factors. Factors are measurable representations of the social values. Selection of factors that accurately capture the richness of overlying social values is again quite difficult, if not impossible. This constitutes the third and most difficult phase of the study. Choosing factors which are appropriate often requires more than one attempt, with continual revision.

For this study, a total of seven factors were originally chosen. After an initial sampling of twenty basin residents, the number of factors was reduced to six. The lists of factors are shown below:

Original Factors for MATS Study

1. Median Annual Household Income in Dollars
2. Riparian Acreage within the Basin
3. Irrigated Acreage within the Basin
4. Urban Population within the Basin
5. Water Table Stability
6. Level of Basin Water Management
7. Distribution of Water Costs

Revised Factor List

1. Median Annual Household Income in Dollars
2. Median Annual Household Income in Dollars in Rural Areas
3. Riparian Acreage within the Basin
4. Urban Population within the Basin
5. Level of Basin Water Management
6. Distribution of Water Costs

This revision was necessary to ensure the factors more completely represent the underlying social values they are intended to represent in measurable form. It is important that the factors should be free of judgmental dependencies, which is to say they should be mutually exclusive. For example, Factor 5 of the original list of factors, Water Table Stability, had to be eliminated because it lacked this needed exclusivity. It could be argued that if stable water

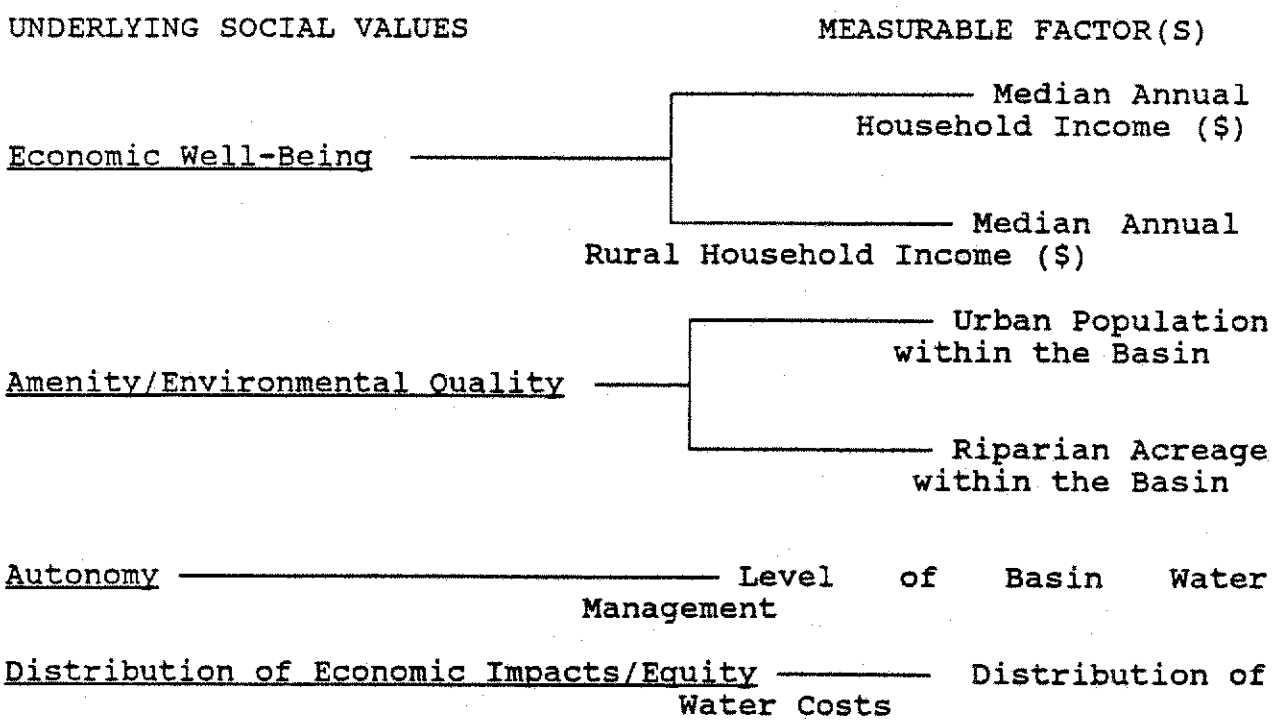
table conditions existed, all the remaining factors become moot. It was to this end that the revised factors were instituted for the second sampling, and the revised factors are described in greater detail below.

Two factors were chosen to measure the social value of economic well-being. The first factor, median annual household income (in dollars), is a measure of the economic prosperity and viability of the basin community and its members as a whole. The second factor, median annual household income in rural areas, is designed to measure the economic viability of non-urban areas of the basin.

The second social value, Amenity/Environmental Quality, also has two measures, or factors. One is the level of urban population in the basin and the other is how much riparian acreage is in the basin. Both of these measures are intended to measure aspects of the environment.

The third and fourth social values each have one factor as a measure. For Autonomy, the factor is whether control over water should reside with local residents, or at a higher level, i.e., the state or federal level. For the Distribution of Economic Impacts/ Equity, the factor is to measure the preferences for how costs of water management should be distributed between the recipients of new water development and basin residents generally. The four social values and the factors are summarized graphically through the use of a simple value tree in the following table.

Figure 34: VALUE TREE



Numerical ranges were then developed for each of the measures and interviews conducted with basin residents selected from the sample list drawn previously. The people interviewed were asked, using the calibrated MATS program, to give their preferences for each of the measures. For example, for the factor of urban population, the range was 25,000 to 150,000, with the current population estimated at 56,000. Residents were asked to specify the preferred population level (function forms), and also to rank urban population in importance relative to the other factors (weights).

The MATS Program then records these preferences by producing function forms and weights. Weighting ranks the factors relative to one another according to each of the participants individual preferences. The MATS program also allows participants to generate a utility function for each factor. This utility function is termed a function form in the language of MATS. In other words, it tells what level of population is preferred or it tells how much riparian acreage is preferred by the participant. These weights and these function forms effectively define the relative importance of relevant social values and also what level (how much) is best. Together, they form the basis for analysis.

Data Analysis

The fourth phase in the process is to analyze the data gathered through the field interviews in order to identify natural grouping tendencies and thus possible interest group divisions within the basin. A statistical technique known as cluster analysis was employed on the data in order to identify natural groupings. A group is any number of study participants who share similar attitudes towards the factors of the MATS model. The word clustering is most synonymous with classification. Properly executed it is a formal, planned, purposeful, or scientific classification. There are several widely used algorithms, or methods available to analyze data for clusters, and the Kmeans algorithm was chosen for use in this study.

Because the factors underwent revision, only those factors common to both rounds of sampling were used in the cluster analysis. Those four common factors are Median Annual Household Income, Riparian Acreage, Urban Population, and Level of Basin Water Management.

The results of the weighting portion of the MATS field surveys, where the thirty study participants ranked the factors relative to one another was subjected to the Kmeans clustering algorithm. Three distinct clusters emerged, one large and two small. Table 7 below briefly summarizes the results.

TABLE 7: CLUSTER ANALYSIS

Clusters	No. of Cases	Variable	Mean
One	5	Income	0.65
		Population	0.14
		Riparian	0.11
		Basin Control	0.10
Two	3	Basin Control	0.48
		Population	0.29
		Income	0.13
		Riparian	0.11
Three	11	Riparian	0.43
		Population	0.23
		Basin Control	0.17
		Income	0.17

The table above indicates the number of participants in each cluster and also the mean value assigned to each factor by all the participants in that cluster. For example, the members of Cluster one place a high emphasis on income with a mean value of 0.65. These mean values indicate the relative importance of the different factors. However, they represent only the factor weighting produced by the MATS program. Analyses of the function forms of the study participants determines within cluster similarities and also differences between clusters. Function forms also determine the preferred factor levels of the study participants. The function forms for two factors, riparian acreage and urban population, provided the greatest opportunity for constructive analysis. The other two factors have function forms of lesser utility because the function form for the factor household income was, as expected, in agreement throughout the study regardless of cluster (everyone would prefer more income to less) and the basin water management factor was presented as a dichotomous variable which did lend itself to discriminant analysis.

Analysis of Clusters

Cluster One: Cluster one mean values indicate a high concern for income, to the exclusion of the other factors. This cluster is defined as representing a fiscally conservative interest group. The function forms for the riparian habitat indicate preference among part of this group for a decrease in the current level, but most expressed preference for current conditions with certainly no expansion. The function forms for urban population show a highest preference for current levels, with some limited preference shown for a high increase in population.

Cluster Two: Cluster two mean values showed a primary concern for basin control over water management and to a lesser extent for urban population. This cluster is defined as representing

an interest group espousing controlled growth and development in the basin. The function forms for riparian habitat show a preference for current conditions to a slight increase, but no decrease. For population levels, this group unanimously preferred a constant and steady increase in population.

Cluster Three: Cluster three mean values indicate the most concern for the riparian acreage. This cluster is representative of an interest group with traditional environmentalist sentiments. The function forms for riparian habitat show a high preference for an increase in the riparian acreage. For population, current conditions are preferred, with little support for substantial increases.

The cluster analysis indicates the presence of at least three distinct water management interest groups in the basin. These three interest groups are defined as **1) Fiscal Conservatives, 2) Pro-Growth and Development**, and **3) Traditional Environmental.** While these interest group definitions are somewhat simplified, they are convenient labels which will be useful in later discussion. These three clusters comprise only 19 of the original 30 study participants, with the other 11 failing to cluster discriminately. This indicates the existence of other more dispersed opinion on the factors within the basin than is indicated overtly through the use of the clustering algorithm.

Evaluation of Plans

The fifth and final phase of the MATS study involves evaluating each of the policy options from the perspective of the values of each of the clusters. A total of ten policy options were generated, and they were entered into the MATS model through the use of plans and impacts. Plans are another word for alternatives or options. Impacts are the effects that plans have on factors. It is this synthesis of the decisionmaker's values as measured through the use of factors, with the available alternatives (plans) to create a ranking of options that forms the final step of the MATS simulation. The following table summarizes the results:

TABLE 8

PLAN EVALUATION

Policy Option*	Cluster One		Cluster Two		Cluster Three	
	Score	Rank	Score	Rank	Score	Rank
1	.612	1	.830	1	.704	2
2-1	.507	10	.351	10	.541	10
2-2	.510	9	.351	9	.544	9
2-3	.513	8	.352	8	.547	8
3-1	.597	4	.827	4	.706	1
3-2	.586	5	.825	5	.703	3
3-5	.556	6	.819	6	.696	6
3-10	.516	7	.810	7	.687	7
4	.609	2	.829	2	.702	5
5	.604	3	.828	3	.703	3

Policy summaries:
1 - Status Quo; 2-1 - Conventional AMA, 150 gpcd, 85% Irrigation Efficiency; 2-2 - Conventional AMA, 150 gpcd, 50% Ag retirement; 2-3 - Conventional AMA, 150 gpcd, 100% ag retirement; 3-1 - AMA, $1.00 per 1000 gal surcharge; 3-2 - Special AMA, $2.00 per 1000 gal surcharge; 3-5 - AMA, $5.00 per 1000 gal surcharge; 3-10 - AMA, $10.00 per 1000 gal surcharge; 4 - Augmentation; 5 - Conservation.

It appears that basin residents would not support the creation of an Active Management Area (AMA) modelled after those already existing in Pima, Maricopa, and Pinal Counties. This is clearly illustrated by the uniformly low plan scores of options 2-1, 2-2, and 2-3 regardless of cluster. This is directly attributable to a strong desire among all study participants to maintain a local level of basin water management, something a state sponsored AMA does not offer.

Cluster One, the fiscal conservatives favor the status quo, but not strongly. Policy Option 4, the augmentation option is the next best alternative for this group. All other options are fairly tightly grouped from a range of .51 to .61. The options least favored by this group are the AMA options, but again, not strongly.

Second, **Cluster Two, pro-development/growth** interests would favor the status quo also, but not strongly. This group rates favorably the policy options 4 and 5, the augmentation and conservation options. There is a larger range among alternatives in this group. Finally, all the AMA policy options are strongly rejected.

Third, **Cluster Three, the environmentalists** would favor Policy Option 3-1, a "Customized" AMA (.71), but also prefer options 4 and 5, the augmentation and conservation options. This group would not, however, favor a conventional AMA, finding it least desirable of all available options.

A number of conclusions can be drawn from the table. First, the status quo, i.e., no new management, appears to fare the best of all the options, ranking first for two clusters and second for the third. However, it should be noted that the status quo policy option enjoys some obvious advantages over the other plans. Perhaps most notable is the fact that this study was limited to a twenty year horizon, and the adverse impacts of retaining status quo management conditions are minimal over this relatively short period of time. While adherence to the status quo may indeed lead to major impacts in the future, and fear that they might do so led to the creation of this report, the factors chosen and the 20 year forecasting horizon do not support this.

Another, more unplanned advantage enjoyed by the status quo became apparent after the original list of seven factors underwent revision. While removing the Water Stability factor eliminated unwanted overlapping amongst the factors, it also eliminated a key indicator of basin resident's values in regard to current water conditions. Throughout the first round of sampling, Water Table Stability ranked consistently among the most important factors, indicating a great deal of concern for current hydrologic conditions within the basin. Participants in the first round of sampling are represented in all three identified interest groups, and Water Table Stability was weighted as important by them all.

STUDY CONCLUSIONS

Some considerations have to kept in mind when looking at the results from any of these policy options. One is that the management models generated data only for the designated period of 20 years. This means that results which might occur in the long range as a result of these scenarios and policies may not be apparent now.

Another effect of the 20-year limitation is that in order to demonstrate the impacts of these policies, it is necessary to assume that policy provisions became effective almost immediately. In reality, most policy provisions are phased-in over a long period of time. For instance, final management plans of the existing AMAs will not become effective until the year 2020, though the Groundwater Management Act was passed in 1980. In the meantime, prior to complete implementation of the policy provisions, the water supply situation in the basin may change, perhaps significantly. It is important to recognize this "time lag" when viewing the model results.

The analyses performed with the four analytical models MODFLOW, MODSIM, WATERBUD, and MATS) have produced the following tentative conclusions:

1) Pumping from the regional aquifer in the Sierra Vista area is depleting stored groundwater reserves there, and accelerated pumping in the future will accentuate this trend unless steps are taken to arrest it. The mean depletion rate is very small, however, when compared with the volume of water in storage in the regional aquifer.

2) Pumping from the regional aquifer is not the major factor imperiling streamflow in the San Pedro River. Drought-related reductions in surface runoff and irrigation-related pumping from the floodplain aquifer are much stronger influences, particularly in the short term. Management of minimum streamflows and maintenance of riparian ecosystems will require control of agricultural pumping and, possibly, the imposition of drought-coping policies.

3) Potential conflict over water management policies in the Upper San Pedro Basin will be rooted in differing value judgments concerning economic and environmental impacts. However, the common desire to maintain local control over water management decisions provides a basis for successful negotiation and policy development.

Directions for Future Policy Development

The University of Arizona study should be considered as only the beginning of the policy planning process for the Upper San Pedro River Basin. The most important contribution of the university effort lies in the analytical tools (MODFLOW, MODSIM, WATERBUD, and MATS) which are now available to assist the necessarily progressive and iterative process of increasing understanding, designing new options, and testing the effectiveness and acceptability of those options.

The options which the university team has described and evaluated are not intended to be real choices for the basin. They were selected of necessity early in the study process, before our understanding of the hydrologic and social processes of the basin reached its present level. But these options do provide insights into the directions which future policy development by the people of the basin might take. It should now be possible to design options which are much more sharply focused upon the basin's real water problems and opportunities.

Three considerations stand out as "musts" for future policy design efforts. The first is the maintenance of water levels in the floodplain aquifer. It is susceptible to short-term impacts, primarily due to drought and irrigation pumping. Long term control of irrigation pumping which is equitable to the irrigators, and a program capable of coping with dry year stresses are high on the list of items worth careful study.

Retiring land from irrigation would reduce ground and/or surface water depletions, depending on the source of the irrigation waters used on that acreage. Most irrigated land lies over the floodplain aquifer and is irrigated from wells; retirement would result in a gain in subflows to surface streams. Regrowth of native vegetation on the retired lands will consume some minor portion of the "saved" water. Retirement within the floodplain aquifer will have the greatest impact on stream flows. Retirement of lands upstream of the RNCA would aid in safeguarding stream flows. Retirement could be achieved by outright purchases of lands, for example by BLM, or by public or private parties interested in safeguarding natural values in the basin.

Irrigation efficiencies can also be increased. For 1990, ADWR currently estimates that irrigation in the upper basin has an average efficiency of 59%, but that an average of at least 80% is physically possible. A 21% increase in efficiency, in principle, should result in a 21% decrease in irrigation-related depletions. Increased efficiencies would result in a gain in subflows to surface streams.

Irrigation efficiencies can be improved through a combination of several technical changes in water conveyance, field delivery, and field preparation. Changes in crops can also result in significant reductions in irrigation needs per acre. The amount of water "saved" by increased efficiencies in irrigation may not reach the 21% theoretical level suggested. Local soil and crop conditions, and other factors, affect actual gains. Also, the type of aquifer will affect whether the increase in efficiency will affect surface water flow. Increased efficiencies can be encouraged and/or required by institutional and/or economic means.

The second policy design consideration is long term control of pumping from the regional aquifer in the Sierra Vista area. The rate of overdraft remains slight when averaged over the entire basin, and major adverse impacts are many years away. Still, it is much easier and less expensive to recognize and begin to deal with it now than it is to wait until the pain begins.

Combined domestic and commercial uses result in just over 21% of depletions. Conservation measures can reduce municipal and rural consumption by as much as 25%, in principle. A reduction in consumption here translates directly into decreased demand for pumping. Further, most domestic and commercial deliveries are from wells in the regional aquifer, with the largest withdrawals occurring in the Sierra Vista-Huachuca City-Fort Huachuca area. Conservation in this urban area would directly reduce withdrawals from the underlying aquifer.

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Outdoor use can be reduced by a variety of xeriscaping methods; indoor use can be reduced through the installation of low-flow plumbing fixtures; use in general can be reduced through educational encouragement of conservative habits. Conservation can be legislated or simply encouraged; if incorporated into plumbing codes, conservation requirements can affect new construction and replacement fixtures in existing construction. Replacement of older fixtures can be accelerated by incentives or other programs. Indoor conservation measures are realtively ineffective in reducing water consumption, however, particularly if effluent reuse is practiced.

Another measure is increased use of effluent. Municipal effluent in the upper basin is used for irrigation of recreational turf and alfalfa, but at very low levels of irrigation efficiency. Municipal treatments presently do not go beyond secondary levels; the effluent is suitable only for watering plants and animals not directly destined for human consumption. Further, the largest proportion of municipal effluent is available in the Sierra Vista-Huachuca City-Fort Huachuca area. Effluent reuse in this area would directly reduce needs for "new" water in this problem area.

Effluent treatment could be carried out with less evaporative loss; the treated effluent could be applied more efficiently, to irrigate more than twice as many acres as is presently being done; the treated effluent could be used for sand & gravel washing; for artificial recharge of the regional aquifer; and it could be conveyed to the main river channels to become surface flow to support riparian habitats if treated to a high enough standard.

Effluent water quality (discharge quality) would have to be improved, if effluent were to be used to irrigate a wider range of crops and/or turfs. In-stream use would require meeting higher chemical, bacterial, and viral quality standards; and would entail substantial conveyance costs. Conveyance of effluent to the San Pedro also would mean removing it from the Sierra Vista-Huachuca City-Fort Huachuca area, where it could be used more effectively for recharge and surface use. Use in the urban area would help with efforts to reduce groundwater withdrawals in that area, which would indirectly benefit subflows to the San Pedro.

The third policy design consideration is the high value placed by all interests on local control of water management decisions. Most water management rules and regulations are now established outside the basin. However, concerted and creative action on the part of basin interests can fill what is still in many respects a policy vacuum. If the people of the basin are successful in developing creative and effective solutions to their own water problems there will be correspondingly less justification and opportunity for those issues to be addresses elsewhere.

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APPENDIX A

TABLE 1. PARAMETERS

I. Inflow from Mexico

Inflow of Surface Water from Mexico
Inflow of Groundwater to Floodplain Aquifer from Mexico
Inflow of Groundwater to Regional Aquifer from Mexico

II. SUB-BASIN NATURAL CHARACTERISTIC (for each sub-basin in U.S.)

Watershed Area Tributary to Streamflow North of Border
Annual Gross Precipitation Watershed
Annual Gross Precipitation Rate over Floodplain
Annual Effective Precipitation Rate over Floodplain
Fraction of Annual Precipitation Falling in Season I
Fraction of Annual Precipitation Falling in Season II
Fraction of Annual Precipitation Falling in Season III
Fraction of Annual Precipitation Falling in Season IV
Runoff Estimator (Moosburner) Equation, Constant Term
Runoff Estimator Equation, Area Exponent
Runoff Estimator Equation, Precipitation Exponent
Area of Regional Aquifer
Steady-State Regional Aquifer Underflow to Next Sub-basin
Average Specific Yield of Regional Aquifer
Start-of-1989 Total Storage in Regional Aquifer
Recharge to Regional Aquifer by Precipitation
Steady-State Elevation of Regional Aquifer Water Table Above Riverbed
1989 Estimated Elevation of Regional Aquifer Water Table Above Riverbed
Area of Floodplain Aquifer
Steady-State Floodplain Aquifer Underflow to Next Sub-basin
Average Specific Yield of Floodplain Aquifer
Start-of-1989 Total Storage in Floodplain Aquifer
Recharge to Floodplain Aquifer by Regional Aquifer
1970-90 Average Sub-basin River Discharge Volume
Steady-State Elevation of Floodplain Water Table Above Riverbed
1989 Estimated Elevation of Floodplain Water Table Above Riverbed
Effective Length of Riverbed
Average Thickness of Riverbed
Discharge Exponent for Estimating Average River Stage
Discharge Coefficient for Estimating Average River Stage
Area of Unvegetated Bare Ground on Riverbed
Bare-Ground Consumptive Use (Evaporation) Coefficient
Discharge Exponent for Estimating Average River Width
Discharge Coefficient for Estimating Average River Width
Open-Water Gross Evaporation Rate
Fraction of Annual Potential Evaporation in Season I
Fraction of Annual Potential Evaporation in Season II
Fraction of Annual Potential Evaporation in Season III

Fraction of Annual Potential Evaporation in Season IV

III. BASIN-WIDE CULTURAL SUPPLY AND DEMAND

Imported Water Recharged to Floodplain Aquifer, Sierra Vista Sub-basin
Imported Water Recharged to Regional Aquifer, Sierra Vista Sub-basin
Export of Water from Floodplain Aquifer, Sierra Vista Sub-basin
Export of Water from Regional Aquifer, Sierra Vista Sub-basin
Imported Water Recharged to Floodplain Aquifer, Benson Sub-basin
Imported Water Recharged to Regional Aquifer, Benson Sub-basin
Export of Water from Floodplain Aquifer, Benson Sub-basin
Export of Water from Regional Aquifer, Benson Sub-basin
Area of River Impoundment in Sierra Vista Sub-basin
Fraction of Impounded River Water Recharged to Regional Aquifer
Fraction Increase in Recharge from Cloud Seeding, Sierra Vista Sub-basin
Fraction Increase in Recharge from Cloud Seeding, Benson Sub-basin

IV. SPECIAL SIERRA VISTA CITY ACTIVITIES

City Use of its Own Wells to Supply Municipal Facilities
Area of Runoff Impoundment in Sierra Vista
Fraction of Captured Runoff Recharged to Regional Aquifer
Fraction of Treated Effluent Diverted to Artificial Wetland
Area of Artificial Wetland
Artificial Wetland Consumptive Use (Evaporation) Coefficient

V. DOMESTIC CONSUMPTION (for fourteen municipal and rural domestic areas: Sierra Vista, SE Sierra Vista suburban area, Huachuca City, Fort Huachuca, Tombstone, Bisbee, Naco, Rural Sierra Vista sub-basin with regulated water delivery, Rural Sierra Vista sub-basin without water delivery, Benson, St. David, Pomerene, Rural Benson sub-basin with regulated water delivery, Rural Benson sub-basin without water delivery.

Census Area Name
Regulated Water Delivery System? (yes/no)
1990 Census Population
Projected Annual Per Capita Population Growth Rate
1980 Median Household Income, $
Number of Water Service Connections, 1989
Acre-Feet of Delivered Water, 1989
Target Water Consumption Rate, Gallons Per Capita Per Day
Fraction of Domestic Water Returned to Basin as Treatable Effluent
Fraction of Effluent Lost to Evaporation During Treatment
Fraction of Treated Effluent Recharged to Regional Aquifer
Fraction of Treated Effluent Used to Supplement In-Stream Flow
Fraction of Households in 1989 with Lowflow Fixtures
Fraction of Older Structures Annually Refitted with Low-Flow Fixtures
Fraction Required Conservation from 1989 Demand
1990 Service Price, $ per 1000 Gallons Delivered
Imposed Additional Water Charges, $ per 1000 Gallons
Seasons I-IV Indoor Use, Demand Equation Coefficient
Season I Outdoor Use, Demand Equation Coefficient

Season II Outdoor Use, Demand Equation Coefficient
Season III Outdoor Use, Demand Equation Coefficient
Season IV Outdoor Use, Demand Equation Coefficient

VI. MISCELLANEOUS DOMESTIC CONSUMPTION PARAMETERS

Price Elasticity, Indoor Domestic Use
Price Elasticity, Outdoor Domestic Use
Income Elasticity, Indoor and Outdoor Domestic Use
Number of Personnel to be Added to Fort Huachuca Staff
Year in Which Above Personnel Will be Added to Fort Staff
Average Number of Additional Family Members Arriving with New Staff
Fraction of New Personnel and Families Who Will Live Off-Base
Estimated Consumption Per Person in Rural Non-Service Areas
Estimated Household Size in Rural Non-Service Areas

VII. AGRICULTURAL CONSUMPTION

Irrigated Acreage, Sierra Vista Sub-basin
Irrigated Acreage, Benson Sub-basin
1989 Irrigation Withdrawals from Floodplain Aquifer, Sierra Vista Sub-basin
1989 Irrigation Withdrawals from Floodplain Aquifer, Benson Sub-basin
Surface Diversion Right, St. David Irrigation District
1989 Actual Surface Diversions, St. David Irrigation District
Surface Diversion Right, Pomerene Irrigation District
1989 Actual Surface Diversions, Pomerene Irrigation District
1989 Average Overall Efficiency, Sierra Vista Sub-basin
1989 Average Overall Efficiency, Benson Sub-basin
1989 Weighted Average Crop Irrigation Requirement, Sierra Vista Sub-basin
1989 Weighted Average Crop Irrigation Requirement, Benson Sub-basin
Weighted Average Effective Precipitation for Irrigation, Sierra Vista Sub-basin
Weighted Average Effective Precipitation for Irrigation, Benson Sub-basin
Long-Term Per-Acre Change in Irrigated Acreage, Sierra Vista Sub-basin
Long-Term Per-Acre Change in Irrigated Acreage, Benson Sub-basin
Required Irrigation Efficiency, Legislated, Sierra Vista Sub-basin
Required Irrigation Efficiency, Legislated, Benson Sub-Basin
Target Weighted Average Crop Irrigation Requirement, Sierra Vista Sub-basin
Target Weighted Average Crop Irrigation Requirement, Benson Sub-basin
Per-Acre Irrigation Demand Equation Coefficient, Sierra Vista Sub-basin
Per-Acre Irrigation Demand Equation Coefficient, Benson Sub-basin
Price Elasticity of Irrigation Demand (for Both Sub-basins)
Imposed Irrigation Well Pumping Tax, $ Per Acre-Foot

VIII. RIPARIAN HABITAT AND MANAGEMENT STATUS

Area of Riparian Vegetation in 1989, Sierra Vista Sub-basin
Area of Riparian Vegetation in 1989, Benson Sub-basin
1989 Salvageable Riparian Acreage, Sierra Vista Sub-basin
1989 Salvageable Riparian Acreage, Benson Vista Sub-basin
Composite Consumptive Use Coefficient, Riparian Vegetation, Sierra Vista Sub-basin
Composite Consumptive Use Coefficient, Riparian Vegetation, Benson Sub-basin
Riparian Corridor Width Equation, First Order Coefficient

Riparian Corridor Width Equation, Second Order Coefficient
RNCA Withdrawals from Floodplain Aquifer, Sierra Vista Sub-basin
RNCA Withdrawals from Regional Aquifer, Sierra Vista Sub-basin
RNCA Withdrawals from Floodplain Aquifer, Benson Sub-basin
RNCA Withdrawals from Regional Aquifer, Benson Sub-basin

IX. INDUSTRIAL CONSUMPTION

1989 Mining Withdrawals from Regional Aquifer, Sierra Vista Sub-basin
1989 Other Industrial Use of Regional Aquifer, Sierra Vista Sub-basin
Fraction of Mining Usage Recharged to Regional Aquifer, Sierra Vista Sub-basin
Fraction of Other Industrial Usage Recharged to Regional Aquifer, Sierra Vista Sub-basin
1989 Mining Withdrawals from Regional Aquifer, Benson Sub-basin
1989 Other Industrial Use of Regional Aquifer, Benson Sub-basin
Fraction of Mining Usage Recharged to Regional Aquifer, Benson Sub-basin
Fraction of Other Industrial Usage Recharged to Regional Aquifer, Benson Sub-basin
Projected Annual Rate of Growth of Mining Consumption
Projected Annual Rate of Growth of Other Industrial Consumption

X. RESERVOIRS AND STOCKPONDS

1989 Area of Runoff-Supplied Impoundments in Sierra Vista Sub-basin
1989 Area of Runoff-Supplied Impoundments in Benson Sub-basin
1989 Area of Groundwater-Supplied Impoundments in Sierra Vista Sub-basin
1989 Area of Groundwater-Supplied Impoundments in Benson Sub-basin
Water Retention Rate for Runoff-Supplied Impoundments
Water Retention Rate for Groundwater-Supplied Impoundments

XI. OPTIONS

Include Riparian Salvage Acres in Total Initial Riparian Acreage?
Model System Without Human Depletions?
Impose Domestic Conservation? (four options)
Include Fort Huachuca in Conservation Efforts?
Impose Target Crop Irrigation Requirements?
Impose Target Irrigation Efficiencies?

TABLE 2. TWENTY-YEAR PROJECTIONS

I. SOCIOECONOMIC CONDITIONS

Population of City of Sierra Vista
Population of Sierra Vista-Southeast Suburban Area
Population of Fort Huachuca
Population of Huachuca City
Population of City of Tombstone
Population of City of Bisbee
Population of Town of Naco
Population of Water Service Areas of Rural Sierra Vista Sub-basin
Population of Non-Service Areas of Rural Sierra Vista Sub-basin
Population of City of Benson
Population of Town of St. David
Population of Town of Pomerene
Population of Water Service Areas of Rural Benson Sub-basin
Population of Non-Water Service Areas of Rural Benson Sub-basin
Median Household Income, City of Sierra Vista
Median Household Income, Sierra Vista-Southeast Suburban Area
Median Household Income, Fort Huachuca
Median Household Income, Huachuca City
Median Household Income, City of Tombstone
Median Household Income, City of Bisbee
Median Household Income, Town of Naco
Median Household Income, Rural Water Service Areas, Sierra Vista Sub-basin
Median Household Income, Rural Non-Service Areas, Sierra Vista Sub-basin
Median Household Income, City of Benson
Median Household Income, Town of St. David
Median Household Income, Town of Pomerene
Median Household Income, Rural Water Service Areas, Benson Sub-basin
Median Household Income, Rural Non-Service Areas, Benson Sub-basin
Household Consumer Surplus, City of Sierra Vista
Household Consumer Surplus, Sierra Vista-Southeast Suburban Area
Household Consumer Surplus, Huachuca City
Household Consumer Surplus, City of Tombstone
Household Consumer Surplus, City of Bisbee
Household Consumer Surplus, Town of Naco
Household Consumer Surplus, Rural Water Service Areas, Sierra Vista Sub-basin
Household Consumer Surplus, City of Benson
Household Consumer Surplus, Town of St. David
Household Consumer Surplus, Town of Pomerene
Household Consumer Surplus, Rural Water Service Areas, Benson Sub-basin
Fraction of Households With Low-Flow Plumbing, City of Sierra Vista
Fraction of Households with Low-Flow Plumbing, Sierra Vista-SE Suburban Area
Fraction of Households with Low-Flow Plumbing, Fort Huachuca
Fraction of Households with Low-Flow Plumbing, Huachuca City

Fraction of Households with Low-Flow Plumbing, City of Tombstone
Fraction of Households with Low-Flow Plumbing, City of Bisbee
Fraction of Households with Low-Flow Plumbing, Town of Naco
Fraction of Households with Low-Flow Plumbing, Rural Sierra Vista Sub-basin
Fraction of Households with Low-Flow Plumbing, City of Benson
Fraction of Households with Low-Flow Plumbing, Town of St. David
Fraction of Households with Low-Flow Plumbing, Town of Pomerene
Fraction of Households with Low-Flow Plumbing, Rural Benson Sub-basin

II. GROSS HYDROLOGICAL AND ECOLOGICAL STATUS INDICATORS

Storage in Floodplain Aquifer, Sierra Vista Sub-basin
Storage in Regional Aquifer, Sierra Vista Sub-basin
Storage in Floodplain Aquifer, Benson Sub-basin
Storage in Regional Aquifer, Benson Sub-basin
Potential Area of Riparian Vegetation in Sierra Vista Sub-basin
Potential Area of Riparian Vegetation in Benson Sub-basin
Average River Stage in Sierra Vista Sub-basin
Average River Stage in Benson Sub-basin
Average River Baseflow Head Difference, Sierra Vista Sub-basin
Average River Baseflow Head Difference, Benson Sub-basin
Period-End Elevation of Floodplain Water Table Above Riverbed, Sierra Vista Sub-basin
Period-End Elevation of Regional Water Table Above Riverbed, Sierra Vista Sub-basin
Period-End Elevation of Floodplain Water Table Above Riverbed, Benson Sub-basin
Period-End Elevation of Regional Water Table Above Riverbed, Benson Sub-basin

III. INFLOWS TO SIERRA VISTA SUB-BASIN

Natural Inputs to Surface Waters in Sierra Vista Sub-basin
Natural Inputs to Floodplain Aquifer in Sierra Vista Sub-basin
Natural Inputs to Regional Aquifer in Sierra Vista Sub-basin
Imported Water Stored in Floodplain Aquifer in Sierra Vista Sub-basin
Imported Water Stored in Regional Aquifer in Sierra Vista Sub-basin

IV. SIERRA VISTA SUB-BASIN LOSSES TO STORAGE

City of Sierra Vista Use of Regional Aquifer
Sierra Vista-Southeast Suburban Area Use of Regional Aquifer
Fort Huachuca Use of Regional Aquifer
Huachuca City Use of Regional Aquifer
City of Tombstone Use of Regional Aquifer
City of Bisbee Use of Regional Aquifer
Town of Naco Use of Regional Aquifer
Rural Sierra Vista Sub-basin Water-Service Areas, Use of Regional Aquifer
Rural Sierra Vista Sub-basin Non-Service Areas, Use of Regional Aquifer
Irrigation Use of Groundwater in Sierra Vista Sub-basin
Mining Industrial Use of Regional Aquifer in Sierra Vista Sub-basin
Other Industrial Use of Regional Aquifer in Sierra Vista Sub-basin
Evaporation from Runoff-Supplied Stockponds & Reservoirs, Sierra Vista Sub-basin
Evaporation from Groundwater-Supplied Stockponds & Reservoirs, Sierra Vista Sub-basin
Phreatophyte Consumption from Floodplain Aquifer in Sierra Vista Sub-basin

Channel Evaporation from Riverbed in Sierra Vista Sub-basin
RNCA Withdrawals from Floodplain Aquifer in Sierra Vista Sub-basin
RNCA Withdrawals from Regional Aquifer in Sierra Vista Sub-basin
Export from Floodplain Aquifer in Sierra Vista Sub-basin
Export from Regional Aquifer in Sierra Vista Sub-basin
Floodplain Aquifer Underflow to Benson Sub-basin
Regional Aquifer Underflow to Benson Sub-basin
Potential Discharge from Floodplain Aquifer to River in Sierra Vista Sub-basin
Available Discharge from Floodplain Aquifer to River in Sierra Vista Sub-basin
River Discharge Volume from Sierra Vista Sub-basin

V. SIERRA VISTA SUB-BASIN RECHARGE AND RETURNS TO STORAGE

Recharge from Regional to Floodplain Aquifer in Sierra Vista Sub-basin
Recharge to Regional Aquifer from City of Sierra Vista
Recharge to Regional Aquifer from Sierra Vista Southeast Suburbs
Recharge to Regional Aquifer from Fort Huachuca
Recharge to Regional Aquifer from Huachuca City
Recharge to Regional Aquifer from City of Tombstone
Recharge to Regional Aquifer from City of Bisbee
Recharge to Regional Aquifer from Town of Naco
Recharge to Regional Aquifer from Rural Water-Service Areas
Recharge to Regional Aquifer from Rural Non-Service Areas
Irrigation Return to Floodplain Aquifer in Sierra Vista Sub-basin
Mining Industrial Return to Regional Aquifer in Sierra Vista Sub-basin
Other Industrial Return to Regional Aquifer in Sierra Vista Sub-basin
RNCA Diversion of Groundwater into River in Sierra Vista Sub-basin
Recharge to Floodplain Aquifer from On-River Impoundment in Sub-basin

VI. INFLOWS TO BENSON SUB-BASIN

Natural Inputs to Surface Waters in Benson Sub-basin
Natural Inputs to Floodplain Aquifer in Benson Sub-basin
Natural Inputs to Regional Aquifer in Benson Sub-basin
Imported Water Stored in Floodplain Aquifer in Benson Sub-basin
Imported Water Stored in Regional Aquifer in Benson Sub-basin

VII. BENSON SUB-BASIN LOSSES TO STORAGE

City of Benson Use of Regional Aquifer
Town of St. David Use of Regional Aquifer
Town of Pomerene Use of Regional Aquifer
Rural Benson Sub-basin Water-Service Areas, Use of Regional Aquifer
Rural Benson Sub-basin Non-Service Areas, Use of Regional Aquifer
St. David Irrigation District Diversions of Surface Water
Pomerene Water Users Association Diversions of Surface Water
Total Irrigation Use of Groundwater in Benson Sub-basin
Mining Industrial Use of Regional Aquifer in Benson Sub-basin
Other Industrial Use of Regional Aquifer in Benson Sub-basin
Evaporation from Runoff-Supplied Stockponds & Reservoirs, Benson Sub-basin
Evaporation from Groundwater-Supplied Stockponds & Reservoirs, Benson Sub-basin
Phreatophyte Consumption from Floodplain Aquifer in Benson Sub-basin

Channel Evaporation from Riverbed in Benson Sub-basin
RNCA Withdrawals from Floodplain Aquifer in Benson Sub-basin
RNCA Withdrawals from Regional Aquifer in Benson Sub-basin
Export from Floodplain Aquifer in Benson Sub-basin
Export from Regional Aquifer in Benson Sub-basin
Floodplain Aquifer Underflow to Lower San Pedro Basin
Regional Aquifer Underflow to Lower San Pedro Basin
Potential Discharge from Floodplain Aquifer to River in Benson Sub-basin
Available Discharge from Floodplain Aquifer to River in Benson Sub-basin
River Discharge Volume from Benson Sub-basin

VIII. BENSON SUB-BASIN RECHARGE AND RETURNS TO STORAGE

Recharge from Regional to Floodplain Aquifer in Benson Sub-basin
Recharge to Regional Aquifer from City of Benson
Recharge to Regional Aquifer from St. David
Recharge to Regional Aquifer from Town of Pomerene
Recharge to Regional Aquifer from Rural Water-Service Areas
Recharge to Regional Aquifer from Rural Non-Service Areas
Irrigation Return to Floodplain Aquifer in Benson Sub-basin
Mining Industrial Return to Regional Aquifer in Benson Sub-basin
Other Industrial Return to Regional Aquifer in Benson Sub-basin
RNCA Diversion of Groundwater into River in Benson Sub-basin

IX. NET HYDROLOGICAL CHANGES

Annual Change in Floodplain Aquifer Storage in Sierra Vista Sub-basin
Annual Change in Regional Aquifer Storage in Sierra Vista Sub-basin
Annual Change in Floodplain Aquifer Storage in Benson Sub-basin
Annual Change in Regional Aquifer Storage in Benson Sub-basin
Annual Change in Floodplain Aquifer Depth to Water Table in Sierra Vista Sub-basin
Annual Change in Regional Aquifer Depth to Water Table in Sierra Vista Sub-basin
Annual Change in Floodplain Aquifer Depth to Water Table in Benson Sub-basin
Annual Change in Regional Aquifer Depth to Water Table in Benson Sub-basin
Annual Change in Discharge of River from Sierra Vista Sub-basin
Annual Change in Discharge of River from Benson Sub-basin
Annual Change in Potential Area of Riparian Vegetation in Sierra Vista Sub-basin
Annual Change in Potential Area of Riparian Vegetation in Benson Sub-basin

X. NET SOCIOECONOMIC CHANGES

Total Population in Upper San Pedro River Basin
Total Irrigated Acreage in Sierra Vista Sub-basin
Total Irrigated Acreage in Benson Sub-basin

San Pedro
Technical Documents
Misc. Reference
Folder 2

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