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AN EVALUATION OF WATER CONSERVATION TECHNIQUES IN THE UPPER COLORADO RIVER BASIN

by

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and
Douglas R. Franklin

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ABSTRACT

The Upper Colorado River Basin states contain large deposits of oil shale, tar sands, crude oil, coal, and natural gas, which are or could be used to produce refined petroleum products, natural and synthetic gas, and electrical power. Agriculture is the predominant water consuming industry of the basin, accounting for 90 percent of the total depletions. Future energy development in the Upper Colorado River Basin will compete with agriculture for the limited supply of water by bidding up the price of water.

The study attempts to identify the need for government-sponsored water conservation measures in conjunction with other water saving techniques employed by the private sectors of the economy in response to increased water prices. The objectives of this study are: 1) To determine the total cost to the economy of the public sector investments in water conservation measures induced by salinity regulations, 2) to select the technological process which optimally allocates water from a social point of view, and 3) to determine which water conservation measures in the agricultural and energy sectors are economically efficient.

A mixed-integer programming model is used to maximize the returns to land, water, and mineral resources of the Upper Colorado River Basin for the agriculture and energy sectors of the economy. The feasibilities of various water saving techniques by industries and of government-sponsored water conservation measures (primarily under salinity regulations) are examined within a benefit-cost analysis framework. The model is solved for the base year 1974, and two future years 1985 and 2000 under increased water demand conditions. Solutions for each of the two future years 1985 and 2000 are obtained for five alternative scenarios.

The results of the model indicate that public investments in water conservation measures are not economically efficient since the marginal value of water is less than the cost of conservation. However, where externalities due to changes in salinity levels are taken into consideration, the value of water is greater than the cost of various conservation programs. This is because the water saved is used for decreasing the salinity levels downstream through greater dilution. Quantitative welfare measures of alternative salinity control policies and the cost-benefit implications toward government-sponsored water conservation programs are derived.

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I. INTRODUCTION

The Upper Colorado River Basin states (Wyoming, Utah, Colorado, and New Mexico) contain large deposits of oil shale, tar sands, crude oil, coal, and natural gas, which are or could be used to produce refined petroleum products, natural and synthetic gas, and electrical power. Agriculture is the predominant water consuming industry of the basin, accounting for 90 percent of the total depletions. With technological advance, population growth and growth of affluence, the demand for water for agricultural and energy uses is expected to increase. Future energy development in the Upper Colorado River Basin will compete with agriculture for the limited supply of water by bidding up the price of water.

Any resulting increase in the price of water will induce agriculture and other water using sectors in the economy to reduce their consumption of water. They will, concurrently, tend to increase the use of substitute inputs in their respective production processes and reduce their use of complimentary inputs.

According to the Water Resources Council (Federal Register 1979), conservation is a reduction in water demand, avoidance of wastes and loss, and improvement of efficiency in the use of water. Accordingly, a price induced reduction in water demand would constitute water conservation. In fact price increases encourage farmers to save irrigation water by employing improvements in water conveyance systems and irrigation methods that provide more uniform water application to the crops. In the energy sector, the demand for water could be reduced by wastewater treatment to permit recycling, mining practices that take maximum advantage of water obtained by mine dewatering, and the use of dry or hybrid cooling towers in power generation.

Given the relative prices of inputs and the cost of factor adjustment, water users can be expected to combine water use with the other inputs in their production processes so that technical and market efficiency conditions are satisfied in the long run. Efficient use is achieved automatically in industries characterized by perfect competition and well-assigned property rights. However, where the water bodies (streams, reservoirs, etc.) are under public ownership, some collective action also may be needed to implement water conservation measures when the value of water increases. For example, water losses that occur in the water course may be reduced at a lower cost than some of the measures that the private water-using sectors might undertake. This establishes a need for collective action under the present legal and institutional framework and criteria for evaluating alternative conservation programs and determining the extent to which conservation programs should be implemented.

In this study, the economic feasibility of a set of water conservation practices that could be undertaken by the government is considered. This set includes various techniques of reducing evaporation in reservoirs and reducing water use by phreatophytes along canals and river banks.

Salinity control provides further motivation for water conservation.

Even if the increases in water demand do not motivate specific conservation techniques, water salvage, or reduction in water use may still be called for. In the subbasins where water quality is relatively good, the result would be to decrease salinity levels downstream through dilution. If the marginal cost of reducing salinity through conservation is less than the resulting marginal benefits of better water quality, conservation measures should be implemented.

The general objective of the study is to identify the need for government sponsored water conservation measures in conjunction with other water saving techniques employed by the private sectors of the economy in response to increased water prices. Other objectives of this study are: 1) to determine the total cost to the economy of the public sector investments in water conservation measures induced by salinity regulations; 2) to select the technological process which optimally allocates water from a social point of view; and 3) to determine which water conservation measures in the agricultural and energy sectors are economically efficient.

A mathematical programming model of resource allocation will be used to maximize the returns to land, water, and mineral resources of the Upper Colorado River Basin for the agriculture and energy sectors of the economy. The feasibilities of various water-saving techniques by industries and of government-sponsored water conservation measures (primarily under salinity regulations) will be examined within a benefit-cost analysis framework.

II. STUDY AREA

The Upper Colorado River Basin is located in the states of Wyoming, Colorado, Utah, New Mexico, and Arizona (Figure 1). The Colorado River rises is the eastern part of the basin in Colorado at an elevation of 13,000 feet and flows in a general southwesterly direction into Arizona through Utah. The Green River, 437 miles long and the largest tributary, begins in the northern end of the basin in Wyoming and passes through eastern Utah. The San Juan River, the second largest tributary, rises in the southwestern part of Colorado and flows westward to join the Colorado River and the main stem in southeastern Utah.

Most of the water flow comes from snow in the mountains. The flow usually peaks in May and then subsides to a base flow near the end of July.

The basin was divided into eight subareas or subbasins (Table 1). As one of the fastest growing energy areas of the United States and, yet, one of the most water-scarce, the Upper Colorado River Basin is ideal for evaluation of the economic and technological issues relating to alternative water conservation technologies.

Agriculture is an important sector in the Upper Colorado Basin. Because of the arid nature of the basin, irrigation is essential for crop production. It consumes over 90 percent of the water used in the basin. Irrigation practices vary from primitive to highly sophisticated. The practices used depend on physical and economic conditions and on institutional arrangements for distributing water supplies. However, unavoidable water losses occur with all methods of water application. Most of the fields are flood irrigated from dirt ditches and furrows; less than 10 percent of the acreage is irrigated by sprinkler systems. This results in "low efficiency" of water use.

The major agricultural activity in the Upper Colorado River Basin is livestock production. Crops are grown primarily for forage and feed. In 1974, hay (alfalfa and native) was the main crop and grown on about 58 percent of the irrigated land. Pasture and small grains ranked second and third. Barley and wheat were the primary grains grown for feed.

An estimated 2.7 million acre-feet of water were applied to cropland in 1974. Irrigation water is only partly used by crops in evapotranspiration. The remainder becomes surface runoff or percolates beyond the root zone and eventually returns to the streams. Loss of water by evapotranspiration concentrates the salt and increases salinity levels. Return flows may also pick up additional salts as they pass through geologic formations in the process of returning to the stream. Hence, irrigation increases salinity downstream by both salt concentrating and salt loading mechanisms. The contribution of irrigated agriculture to the salinity has been estimated to be between 17 and 37 percent in the Upper Colorado River Basin (Utah State University 1975). Any change in water use within or water transfer from the agricultural sector, through its effect on water quality, can potentially affect energy development decisions in the basin and water use in the Lower Basin.

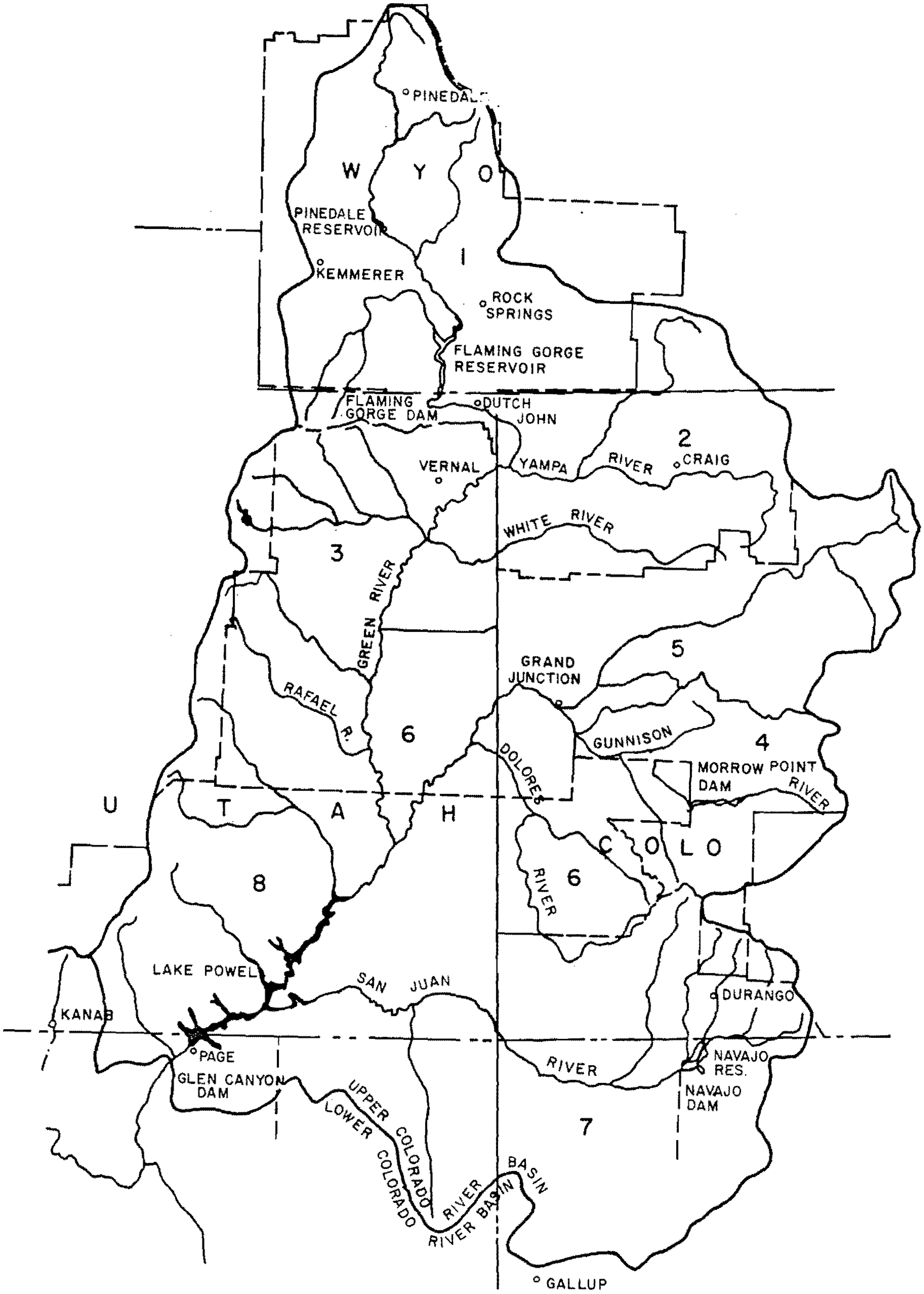

Figure 1. Upper Colorado River Basin (numbers indicate subbasins).

Table 1. Major characteristics of the Upper Colorado River Basin.

Subbasin	Geographic Area	Counties	Major Towns	Major Lakes and Rivers
1	Southwestern Wyoming	Lincoln Sweetwater Sublette Uinta	Green River (WY) Kemmerer Rock Springs	Flaming Gorge Reservoir Green River
2	Northwestern Colorado	Moffat Rio Blanco Routt	Craig Meeker	White River Yampa River
3	Northeastern Utah	Carbon Daggett Duchesne Emery Uintah	Green River (UT) Price Roosevelt Vernal	Flaming Gorge Reservoir Duchesne River Green River Price River White River
4	South Central Colorado	Delta Hinsdale Gunnison Ouray	Delta Montrose	Blue Mesa Reservoir Gunnison River Marrow Point Reservoir Crystal Reservoir
5	Central Colorado	Garfield (CO) Grand (CO) Eagle Mesa Pitkin Summit	Grand Junction Rifle	Colorado River Gunnison River
6	East Central Utah West Central Colorado	Grand (UT) Dolores Montrose San Miguel	Moab Montrose	Colorado River Dolores River
7	Southwestern Colorado Northwestern New Mexico	Archuletta La Plata Montezuma San Juan (CO) San Juan (NM)	Durango Bloomfield Farmington	Navajo Reservoir San Juan River
8	Southwestern Utah	Garfield (UT) Kane San Juan (UT) Wayne	Bluff Monticello	Lake Powell Colorado River San Juan River

The Upper Colorado River Basin contains a vast supply of energy resources including coal, oil shale, oil, natural gas, uranium, tar sands, hydropower, and geothermal resources. At present, the most important commercially are coal, oil, and natural gas. The recent shortage of energy has fostered the expansion of old sources and exploration for new sources.

Major deposits of oil shale are located in subbasins 2, 3, and 5; and tar sand is located in subbasins 3, 6, and 8. Any development of the oil shale resources will be located on the White River in Utah and Colorado and on the Colorado River between Rifle and Grand Junction, Colorado. Coal gasification is a potential energy industry planned for New Mexico and Wyoming. Additional steam electric power generating plants are planned within most of the subbasins.

The development of these resources depends largely upon economic feasibility and regulations to control environmental impacts. Water supplies and water quality are likely to be affected if large-scale energy development occurs. Although each energy production process demands a different quantity, water is an important input to the development of all energy sources.

Water pollution problems arising from the production of various energy related products are also of major concern. Sources of pollution include surface disturbances producing sediments and salt, mine drainage producing heavy metals and other toxics, wastewater discharges containing organic and carcinogenic agents, and temperature increases from using water for cooling. Moreover, the energy industries' large diversion and consumptive use of water decreases the stream's capacity for assimilating those discharges.

The extent to which energy development occurs will, therefore, depend to a large degree on the sector's ability to acquire water, either through purchases from agriculture or acquisitions of rights to any unappropriated water (which may not exist). The technical choices relating to in-plant water use, disposal of plant effluents, technical production processes, and response to regulations on effluents are other primary factors which will determine the feasibility of energy development.

In order to probe more fully the interrelations between economic development and the availability and quality of water, this study investigates the relative costs, water requirements, and impacts of various technical choices available to the agricultural and energy sectors. Alternative measures to reduce water losses and wastes that can be implemented by the government sector are also studied.

III. WATER CONSERVATION TECHNIQUES

A presidential policy statement made in May, 1977, declares that the federal water policy should be revised "with water conservation as its cornerstone." In response, the Comptroller General of the United States (1977), the Commission on Natural Resources Ad Hoc Committee on Water Resources (1978) and the Office of Science Technology and Policy (1978) produced water conservation studies.

The Comptroller General underscored the need for a coordinated effort on the part of local, state, and federal governments to reduce losses from irrigation conveyance systems. The Commission on Natural Resources summarized five consultants' reports covering water conservation techniques in agriculture, municipal, industrial, and steam electric power and stressed the need for more research. The Office of Science and Technology Policy presented 12 water resource policy issues and discussed policy recommendations and directions for research in each category. The report stated that greater water use efficiency is needed in irrigation.

Water use can be reduced in agriculture by a variety of methods. Possibilities range from shifting to a less water intensive crop to improvement of conveyance systems. Investments in conservation measures can reduce water losses by reducing evaporation during transport both on farm and off-farm and by transpiration by vegetation growing along canal banks. Appropriate irrigation scheduling and investment in irrigation systems such as sprinklers permit more effective and uniform water applications to crops. This could increase the yield and, thus, provide substantial gains to the farmers, while increasing the average product of water.

The technology is also available to decrease water consumption in energy production processes. Abbey (1979), Probstein and Gold (1978), and Keefer and McQuivey (1979) discussed rates of water use in energy production under alternative technologies. Specifically, Abbey estimated water consumption for dry tower cooling, wet tower cooling, and hybrid cooling (combination of wet tower and dry tower cooling) using 2, 10, 20, and 40 percent wet tower cooling. Probstein and Gold estimated water consumption for several conversion processes in coal gasification, coal liquefaction and oil shale production. In their article, Keefer and McQuivey give water availability and water consumption estimates for tar sands development in Utah. Their water consumption figures are not based on actual measurements. The literature contains water requirement estimates which range widely for the same technology. In this study, the most common estimate and sometimes the average of the water consumption estimates of several reports was used.

As an example, Abbey (1979) discusses several options available to energy producers and developers for substitution for water. These include dry cooling, which reduces the water requirement of electric power generation plants from 5,000-20,000 acre-feet per year to 1,000-2,000 acre-feet per year per 1,000 MW, and hybrid cooling, which combines dry and wet tower cooling. The costs of a dry or a hybrid cooling system are very high when compared to the value of water in agriculture. Abbey estimated the opportunity cost of water saved for a 100 percent dry cooling system at $5,500 per acre-foot. For a 40 percent wet system, cost is estimated at $870 per acre-foot of water saved. When compared to the agricultural value of water which ranges from $5 to $20 per acre-foot (which is approximately what the farmers pay in most regions) depending on the soil, crops, etc., the energy sector can buy water from agriculture at much less cost than it can install dry cooling in power generation. Also, the degree of water conservation depends on the prevention of seepage and evaporation losses from evaporation ponds, the amount of reuse of treated wastewater, and the use of saline water technology.

Phreatophytes, which are deep-rooted, high water use plants, occupy the floodplains and canals over much of the western United States. Robinson (1952) estimated that phreatophytes occupy over 15 million acres and consume 25 million acre-feet annually in the 17 western states. Horton and Campbell (1974), in a USDA Forest Service research paper, estimated that if 4 million acres of phreatophyte growth were treated, 4 to 8 million acre-feet per year of water would be added to western stream flow.

Most phreatophytes have a low economic value. In recent years, however, there has been increasing interest in wildlife habitat, fish habitat, recreation, and the aesthetic values attributed to the phreatophyte areas. A program for phreatophyte elimination must take into account the economic value lost (Horton and Campbell 1974). Although between 1 and 2 acre-feet per acre of water consumed by phreatophytes could be salvaged, the cost may not be justified in all locations (Robinson 1958).

Along the 437 mile course of the Green River, about 40,000 acres of floodplains are covered by phyreatophytes. The average daily depletion in stream flow for a 21-day period in September, 1948, was calculated to be 552.4 acre-feet (Robinson 1958). If this figure can be regarded as an average, then about 201,626 acre-feet of water or 4.4 percent of the Green River stream flow at Green River, Utah, is consumed by phreatophytes annually. That is two times the amount of water proposed for development by the Bonneville Unit of the Central Utah Project. Koogler (1952) and Cramer (1952) give methods of control for phreatophytes and their associated costs. The methods include 1) mechanically and/or chemically preventing plant growth through mowing and spraying and 2) removing the water supply by pumping, channelization, or lining or piping water around phreatophyte growth. Residual evaporation by phreatophytes and the ground surface could still occur.

Evaporation suppression on reservoirs has been researched throughout this century. The Bureau of Reclamation has had a lead role since 1958. A detailed literature review is found in Hughes et al. (1974). Their report summarizes studies on the effectiveness of existing techniques for surface retardation of evaporation and evaporation suppression by reservoir destratification.

By analyzing these potential water conservation practices in an overall economic framework, water policy planners are provided a basis for projecting the impacts of energy and agricultural growth on water allocation, water quality, and water quantity within the Upper Colorado River Basin. The results should help in formulating a policy that will enable future users of water to make more effective utilization of the water resources.

IV. ECONOMIC ANALYSIS AND MODEL DESCRIPTION

Economic Analysis

The modeling used in this study is based on analysis of market response to an increase in water price and the implications for resource allocation. This analysis, in addition to predicting the response of the private water-using sectors, provides a setting for analysis of the justification for collective action in water conservation measures. Welfare effects are discussed in this abstract exposition.

Consider a representative water-using industry A, perhaps the agricultural sector. In Figure 2(a), the downward sloping curve D^A_{SR} denotes the value of the marginal product of water (VMP ^{A}) for A. This curve is the short-run demand for water. For various prices of water, it represents the maximum quantity that would be demanded by A to produce a profit-maximizing level of output while not changing the level of any of the other inputs used in the production process.

value of the marginal product of water (VMP) for A. This curve is the short-

In Figure 2(b), the initial aggregate demand curve for all water-using sectors is given by D_0. Let S_{SR} at quantity X_0 represent the aggregate supply which is assumed to be fixed in the short-run. The prevailing market price P_0 is given by the intersection of S_{SR} and D_0.. In Figure 2(a), the quantity of water demanded by industry A is given by Q_0.

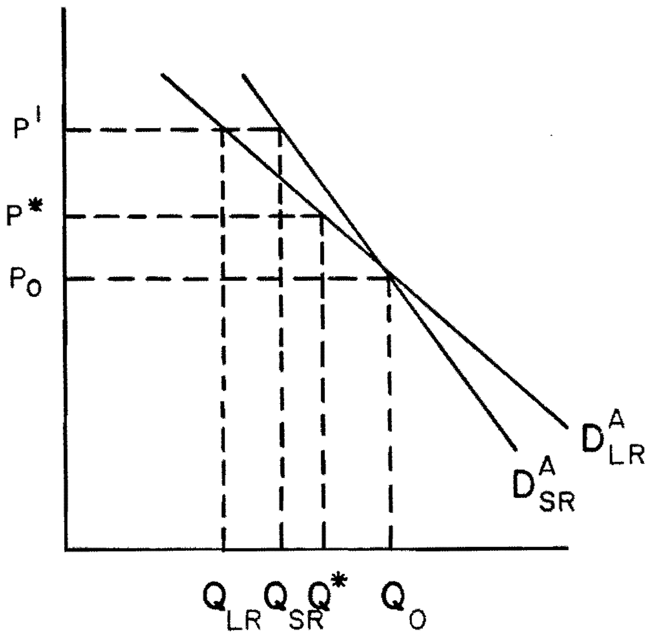

Figure 2(a). Industry water demand.

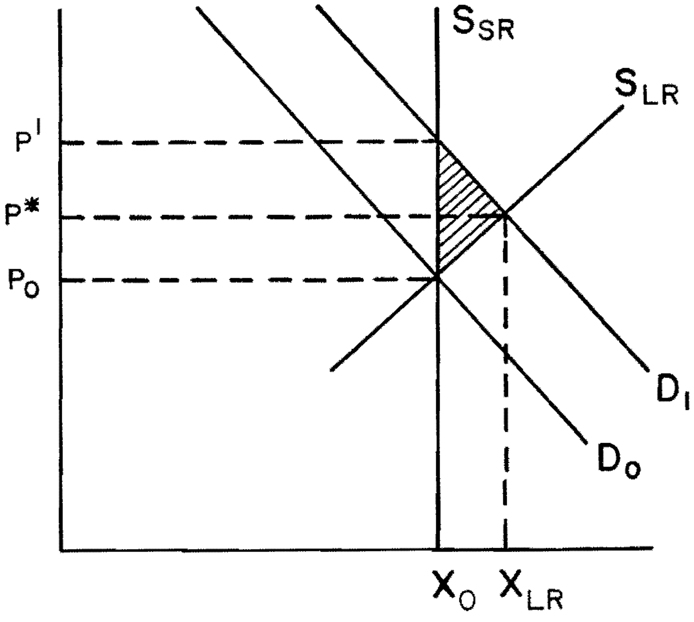

Figure 2(b). Aggregate water demand and supply.

With the addition of a second sector, for example anticipated energy developments, let the aggregate demand for water increase to D_1 as in Figure 2(b). The new price will be P^1. In the short-run, this change in price will cause industry A to move along the VMP curve D^A_{SR} and reduce its quantity of water used to Q_{SR} in Figure 2(a). In the short-run, the reduction in water use will depend upon the change in the price of water and the elasticity of the marginal value product (VMP) of water. For a given price change, the more elastic the VMP curve is, the greater will be the reduction in water use. The percentage reduction in water use can be estimated by multiplying the percentage increase in price by the elasticity of the VMP of water.

In the long-run, however, water demand is more elastic than in the short-run. An increase in the price of water will increase the use of substitute inputs and decrease in the use of complementary inputs. After factor adjustments take place, the VMP of water will decline from the previous level. The reduction in water use in the long-run will therefore be greater than that in the short-run because water uses have time to adjust. In the long-run, given A time to adjust the level of all other inputs, water use will move along the long-run demand curve D^A_{LR}. At price P^1, the quantity of water demanded Q_{LR} is smaller than Q_{SR} as a result of greater use of substitute inputs in the production process in response to the increase in the water price. The change in input mix between water and other factors of production constitutes adoption of water conservation technology. A large reduction in water use by all industries could bring down the demand for water and hence the price. Consequently, water conserving processes partially counteract the price increase for water caused by an increase in development.

Consider the supply of water. In the short-run, the water supply is shown as fixed at X_0. The supply in the long-run S_{LR} will be generally more elastic than in the short-run. Although the amount of water physically available is finite, the quantity of water that can be used effectively can be increased by alternative techniques in water conservation measures. The marginal resource cost of supplying various levels of water by reducing losses occurring in the natural water course is represented by S_{LR}. If D_1 in Figure 2(b) represents the aggregate demand, by adopting conservation measures, the price of water P* is found at the intersection of S_{LR} and D_1. At the new lower price P*, the corresponding quantity of water used by industry A is Q*.

Under present legal and institutional arrangements, many such conservation measures can be sponsored as government projects. The amount of water salvaged from these projects is represented by X_0X_{LR}. The shaded area in Figure 2(b) can be used to estimate the potential welfare gain to the society resulting from the government's investment in water conservation measures.

Empirical analysis to estimate a quantitative gain, however, requires information on demands and supplies for the study area for the short- and long-run. Moreover, water quality regulations and agreements among Upper Colorado River Basin states and the Colorado River Basin Compact need to be considered as constraints in the analysis. In order to incorporate these features, a mathematical programming model is formulated to identify the benefit-maximizing level of conservation measures under various scenarios.

Description of the Optimization Framework

The study area was subdivided into eight water resources subareas (WRSA) as shown in Figure 1. A two-sector mixed-integer programming model consisting of agricultural production and probable energy activities was formulated for the basin. The four submodels contained in this formulation are an agricultural production model, an energy production model, a water resources model, and a salinity model.

The agricultural commodities produced are alfalfa, small grains, corn silage, potatoes, and pasture. The net returns to agriculture are defined as the proceeds from the sale of the final outputs less the total variable production costs. The relevant constraints for this submodel are the present and potential availability of different classes of irrigable lands and various crop rotations.

The energy submodel includes production, conversion, and transportation of energy materials. Specifically, the activities considered are the production of crude oil, natural gas, and oil-shale, the refining of petroleum, surface and underground mining of coal, coal-fired electric power generation, and coal slurry. The net returns to the energy sector are defined as the gross revenue from the sale of final energy outputs less the costs of extraction, conversion and interregional transportation. The relevant constraints for this submodel include interregional energy flows, resource availabilities and plant capacities of the conversion facilities.

The water resource model consists of a set of constraints that restricts the combined use of water in agriculture and in energy to be less than or equal to the availability of water in each subbasin less fixed requirements for other uses such as municipal, wetlands, and transbasin diversions including exports for the other uses in existing or planned projects. Further, the total consumptive use in each state is limited by the Colorado River Basin Compact amounts. Specifically, the allocation of water amoung Colorado, New Mexico, Wyoming, and Utah was restricted such that the individual state shares would be no more than 51.75, 11.25, 23.0, and 14.0 percent, respectively, as dictated by the compact.

The salinity model is based on a mass-balance approach. The total natural salt inflow into any given WRSA is first calculated. The amount of salt removed with water depletions for all uses is subtracted from this quantity. The additional salt loadings from the irrigation return flows are then added to determine the total salt outflow from each WRSA. These are sequentially added to give the total salt loading at Lees Ferry. Both the outflow of water and salt at Lees Ferry are variables determined within the model. For specific scenarios of the analysis, the constraint on the concentration of salt at any point is set by letting the ratio of the outflow of salt to water be less than or equal to a desired level. This constraint could have been expressed as a linear inequality for a given level of concentration by appropriately rearranging terms. Alternately, since the percentage change in concentration is equal to the difference in percentage changes in total dissolved solids (TDS) and the outflow of water (for small changes, the second order terms are negligible), this constraint is expressed as a linear inequality in changes in concentration.

The agricultural production model includes three methods for transporting water to the crops. These are unlined ditches, lined ditches, and pipes. Water savings and the associated costs were estimated for each improvement. Surface and sprinkler irrigation methods are similarly considered in the model.

In the energy production model, several alternative water use technologies are considered. Wet towers, 40 percent wet towers, 10 percent wet towers, and dry towers are considered as specific cooling systems in power generation. For tar sands, surface extraction and in situ retorting are included.

Oil shale production activities include both surface and underground extraction as well as in situ retorting. Coal gasification processes included in the model are lurgi, synthane, and synthoil processes. Only one of these processes is allowed to be selected at any potential site through integer constraints. However, the scales of the projects are allowed to be continuous variables.

Two major water conservation measures are incorporated in the water resources submodel. The first, reservoir evaporation suppression, considered two activities in the model--use of monomolecular film and reservoir destratification. The relevant costs and water salvage are used. The second conservation measure involved the reduction of water use by phreatophytes along river and canal banks. Sparse growth spraying, dense growth spraying, mechanical clearing and canal lining are used in the model as activities.

The objective function for the mixed-integer programming model was the sum of the net returns to agriculture and energy. Maximization of this objective subject to the relevant constraints is the basis for this analysis. The solution to this programming model gives the appropriate production processes, water-use techniques, and the various conservation measures to be implemented.

V. MODEL DATA DEVELOPMENT

The agricultural and energy sector production coefficients, water availability, water quality, water consumptive use, and economic and market data were derived from several sources. The data for the basic model are developed in Narayanan et al. (1979) and Keith et al. (1978).

Water Resources

Water Availability

Water shares for the Upper Basin states are estimated for 14.9 and 13.8 million acre-feet total availability assumptions. The flows for each subbasin are derived from hydrologic and stream gage data within each subbasin (USGS Water Data Reports for Wyoming, Colorado, New Mexico, and Utah, for selected years) as explained by Bishop and Narayanan (1979) and Padungchai (1980). Table 2 indicates the resulting estimates of net water available for irrigation and energy use by subbasin.

Water Quality

The salinity concentration level associated with tributaries of each subbasin is a weighted average of the salt divided by the water flow from the hydrologic units originating within a given subbasin. The estimated salt and flow by hydrologic unit are obtained from Padungchai (1980). The salinity control projects authorized and planned by the Bureau of Reclamation and their effects as estimated in Narayanan et al. (1979) were used in this analysis.

Current and Future Water Uses

Current and projected levels of depletions for municipal, industrial, export, and other purposes for 1985 and 2000 are based on U.S. Water Resources Council (1977) and Narayanan et al. (1979). Water availabilities for each subbasin in the model are derived by subtracting current and future water uses from the water supply for annual and summer flows.

Agricultural Activities

Nine irrigated crops are selected for consideration in the study area. They are alfalfa and other hay (full and partial irrigation), barley, wheat, oats, nurse crops, corn silage, corn grain, potatoes, and pasture.

Objective Function Coefficients

The annual prices, crop yields, costs of production, and net returns are obtained from Padungchai (1980) and Narayanan et al. (1979). Ten percent higher yields were used for sprinkler irrigation to indicate that yields increase as application uniformity improves (Frickel 1980; Cummings et al. 1977; Franklin 1978). Tables 3 and 4 show the estimated crop yields and net returns per acre for sprinkler irrigated crops. Most of the data used in this study are secondary data. The details of all data sources are given in Narayanan et al. (1979). Where data were not available for specific subregions, average for the entire Upper Basin was used.

Land

Current actual irrigated acreages and projected increases in irrigated agricultural land are used in the analysis as taken from Padungchai (1980).

Table 2. Net water available for irrigation and energy uses in each subbasin under alternative water supply assumptions (AF x 10^3).

Sub-basin	1975			1985			2000		
	Case 1[a]	Case 2[a]	Summer Flow	Case 1	Case 2	Summer Flow	Case 1	Case 2	Summer Flow
1	1,773.5	1,628.7	1,168.6	1,670.2	1,525.4	1,063.5	1,492.6	1,347.8	929.7
2	2,213.2	2,025.4	1,560.8	2,203.6	2,015.8	1,509.5	2,187.9	2,000.1	1,481.8
3	1,072.6	970.4	507.1	923.6	821.4	417.1	914.3	812.1	408.0
4	2,250.1	2,075.5	1,452.4	2,249.3	2,074.7	1,410.7	2,247.3	2,072.7	1,394.4
5	3,381.3	3,065.9	2,308.4	3,133.3	2,817.9	2,061.6	3,070.7	2,755.3	1,994.4
6	648.8	594.0	257.8	546.8	492.0	207.5	543.8	489.0	204.0
7	2,315.2	2,136.2	1,248.9	2,287.1	2,108.1	1,197.6	2,286.3	2,106.3	1,184.4
8	441.6	406.0	190.6	439.0	403.4	184.0	436.1	400.5	180.8
Total	14,096.3	12,902.1	8,694.6	13,452.9	12,258.7	8,051.5	13,179.0	11,984.8	7,777.5

[a] Case 1 refers to virgin flow assumption of 14.9 million AF and Case 2 refers to the flow assumption of 13.8 million AF.

Source: Narayanan et al. (1979) and USGS Water Data Reports for Wyoming, Colorado, New Mexico, and Utah.

Table 3. Estimates of annual crop yields per sprinkler irrigated acre.

Subbasin	Alfalfa		Barley bu	Wheat bu	Oat bu	Nurse Crop bu	Corn Grain bu	Corn Silage tons	Potato CWT	Pasture AUM
	Full tons	Partial tons								
1	3.865	3.003	55	55	55	55	35.62	14.41	96.25	4.95
2	3.542	3.135	55	55	55	55	107.338	16.918	67.21	7.48
3	3.865	3.344	68.7	55	68.2	55	60.973	13.75	116.93	7.48
4	3.865	3.444	60.5	55	55	55	109.78	18.084	49.93	7.48
5	3.865	3.444	61.7	55	55	55	107.338	16.918	160.27	7.48
6	4.595	3.553	68.2	55	55	55	96.404	19.492	233.618	7.48
7	3.729	2.684	55	55	55	55	96.404	12.98	99.275	7.48
8	3.729	2.684	68.7	55	68.2	55	-	11.825	171.875	7.48

Irrigation and Agricultural Water Consumptive Use Coefficients

The coefficients for irrigation efficiency, the costs of sprinkler systems and canal lining, and the yearly averages of water consumptive use (in acre-feet) for each crop in each subbasin are obtained from Keith et al. (1978), Narayanan et al. (1979), and Padungchai (1980). A 10 percent higher level of consumptive use was used for sprinkler irrigation to reflect the increase in yields resulting from the utilization of this technology (see Frickel, Cummings et al.). Table 5 shows the consumptive use by subbasin for sprinkler irrigated crops.

Energy Activities

Energy sector production is divided between natural energy outputs and final outputs. The natural energy outputs include underground and strip mined coal, petroleum, natural gas, crude oil from oil shale, and crude oil from tar sands. The final outputs are converted from natural energy outputs. These include electricity from coal-fired electric generation plants and nuclear power plants, synthetic natural gas from coal gasification facilities, and refined oil products.

Objective Function Coefficients

The prices of coal by county and by state, the prices of crude oil and natural gas at the well head, shale oil prices, prices of refined products from crude oil, prices of crude oil from tar sand, and coal gasification prices and the associated operating costs are reported in Padungchai (1980), Narayanan et al. (1979), and Keith et al. (1978).

The average prices of electricity were obtained from Narayanan et al. (1979). Cost data for alternative cooling technologies were obtained from Hu et al. (1978) and U.S. Environmental Protection Agency (1979). The average price, cost and net returns under alternative water conservation technologies are given in Table 6 for coal-fired power generation and in Table 7 for nuclear power generation in the subbasin in which those methods are used or contemplated.

Alternative cost information for various oil shale, coal gasification, and tar sand developments is obtained from Probstein and Gold (1978) and Keefer and McQuivey (1979).

The final outputs of energy activities can be transported by rail or truck for coal and by pipeline or tank car for petroleum. The transportation costs are obtained from Narayanan et al. (1979).

The Energy Conversion Process Efficiency

When the natural energy products are converted to final outputs, losses occur in the conversion process. Energy conversion process efficiencies were used as derived in Keith et al. (1978) and Narayanan et al. (1979).

The Energy Water Consumptive Use Coefficients

The major sources of data on consumptive use were Narayanan et al. (1979), Keefer and McQuivey (1979), U.S. EPA (1979), Colorado Department of Natural Resources (1979), Hu et al. (1978), Keith et al. (1978), and Probstein and Gold (1978). The estimates of water requirements for energy production are given in Table 8.

Energy Production Capacities and Resource Availabilities

The current and future planned energy production capacities for natural and final energy outputs were obtained from Narayanan et al. (1979) and Padungchai (1980).

Table 4. Net annual returns of sprinkler irrigated crops per acre (dollars per acre).

Subbasin	Alfalfa Full tons	Alfalfa Partial tons	Barley bu	Wheat bu	Oat bu	Nurse Crop bu	Corn Grain bu	Corn Silage tons	Potato CWT	Pasture AUM
1	126.22	91.02	142.92	144.37	51.85	33.53			162.56	97.20
2	122.36	109.46	75.64	135.57	67.80	80.28			127.59	97.39
3	122.84	106.50	91.67	144.92	90.79	85.22	159.83	203.62	267.63	97.39
4	140.07	121.31	75.64	135.57	75.74	80.28	228.42	194.73	94.40	97.39
5	140.07	121.31	75.64	135.57	102.12	80.28	223.35	174.67	304.33	97.39
6	140.98	117.52	65.64	135.57	88.70	40.95	200.59	218.94	443.60	97.39
7	125.68	90.47	65.64	135.53	71.02	40.95	200.59	186.40	188.52	97.39
8	118.64	85.40	91.67	144.92	67.80	85.22		203.62	493.39	97.39

Table 5. Annual consumptive use (acre-feet per acre) during an average growing season for sprinkler irrigation.[a]

Subbasin	Alfalfa Full tons	Alfalfa Partial tons	Barley bu	Wheat bu	Oat bu	Nurse Crop bu	Corn[b] Grain bu	Corn[b] Silage tons	Potato CWT	Pasture AUM
1	2.31	1.21	1.32	1.837	1.76	1.76	-	-	1.925	1.925
2	2.145	0.99	1.32	1.837	1.76	1.76	-	-	1.925	1.87
3	2.31	1.21	1.32	1.837	1.76	1.76	2.288	1.54	1.925	1.98
4	2.2	1.1	1.32	1.837	1.76	1.76	2.288	1.43	2.013	1.87
5	2.2	1.1	1.32	1.837	1.76	1.76	2.288	1.43	2.013	1.87
6	3.08	2.09	1.54	1.837	1.76	2.2	2.288	1.98	2.013	2.42
7	2.09	0.99	1.43	1.837	1.76	1.76	2.288	1.98	2.013	2.2
8	2.09	0.99	1.43	1.837	1.76	1.76	-	2.288	2.013	2.2

[a] Consumptive use for sprinkler irrigated crops is estimated to be 10 percent higher than non-sprinkler irrigated crops due to higher yield and uniformity of water application.

[b] Missing numbers indicate that the crop is not grown in significant amount in the subbasin.

Table 6. Average price, cost and net return (dollars per MWH) of electricity for alternative cooling technologies by subbasin for coal fired power generation.

Subbasin	Cooling Technology	Price	Cost	Net Return
1	Wet Tower	16.12	7.09	9.03
	40% Wet	16.12	11.16	4.96
	10% Wet	16.12	13.12	3.00
	Dry Tower	16.12	18.78	-2.66
2	Wet Tower	21.19	7.56	13.63
	40% Wet	21.19	12.39	8.80
	10% Wet	21.19	15.10	6.09
	Dry Tower	21.19	20.13	1.06
3	Wet Tower	16.12	8.79	7.33
	40% Wet	16.12	13.57	2.55
	10% Wet	16.12	14.66	1.46
	Dry Tower	16.12	19.98	-3.86
6	Wet Tower	21.71	11.78	9.93
	40% Wet	21.71	16.38	5.33
	10% Wet	21.71	19.06	2.64
	Dry Tower	21.71	24.10	-2.39
7	Wet Tower	21.71	11.78	9.93
	40% Wet	21.71	16.38	5.33
	10% Wet	21.71	19.06	2.64
	Dry Tower	21.71	24.10	-2.39
8	Wet Tower	16.12	8.79	7.33
	40% Wet	16.12	13.57	2.55
	10% Wet	16.12	14.66	1.46
	Dry Tower	16.12	19.98	-3.86

Source: Narayanan et al. (1979) and Hu et al. (1978).

Note: Due to the quality and quantity of coal and water and the environmental constraints imposed on once-through cooling for electric generation, it is assumed that once-through cooling technology will not be utilized within the Upper Colorado River Basin.

Table 7. Average price, cost and net return (dollars per MWH) of electricity for alternative cooling technologies by nuclear power generation in subbasin 3 for the year 2000.

Subbasin	Cooling Technology	Price	Cost	Net Return
3	Wet Tower	16.12	7.48	8.64
	40% Wet	16.12	13.15	2.97
	10% Wet	16.12	16.77	-0.65
	Dry Tower	16.12	22.60	-6.48

Source: Hu et al. (1978).

Table 8. Estimate of water requirement for energy production.

Energy Activity	Water Requirement	
Underground coal mining	344 AF/10^6 tons	
Strip coal mining	204 AF/10^6 tons	
Crude oil	53.1 AF/10^6 bbls	
Natural gas	1.67 gallons/MSCF	
Tar sands - surface extraction	61.38 AF/10^6 bbls	
Tar sands - in situ retorting	644.1 AF/10^6 bbls	
Oil shale - surface extraction	13,400-20,100 AF/yr	for a 50,000 bpd production facility
Oil shale - underground extraction	6,800-10,600 AF/yr	
Oil shale - in situ retorting	3,000-5,700 AF/yr	
Oil shale - modified in situ	5,000-8,000 AF/yr	
Coal gasification - lurgi process	5,600-9,000 AF/yr	for a 250 mmcfd production capacity
Coal gasification - synthane process	6,694-10,500 AF/yr	
Coal gasification - synthoil process	9,655-13,000 AF/yr	
Oil refinery	43 gallons/bbl	
Coal fired electric generation		
- wet tower cooling	9.0491-12.200 AF/yr/MW	
- 40% wet tower cooling	3.6179-4.4063 AF/yr/MW	
- 10% wet tower cooling	0.9023-1.1038 AF/yr/MW	
- dry tower cooling	0 AF/yr/MW	
Nuclear power electric generation		
- wet tower cooling	17.0123-19.3946 AF/yr/MW	
- 40% wet tower cooling	6.1457-7.4022 AF/yr/MW	
- 10% wet tower cooling	1.4900-1.8571 AF/yr/MW	
- dry tower cooling	0 AF/yr/MW	

Source: Narayanan et al. (1979); Keith et al. (1978); U.S. EPA (1979); Hu et al. (1978); Probstein and Gold (1978); and Colorado Department of Natural Resources (1979).

Non-Agricultural and Non-Energy Activities

The non-agricultural and non-energy activities represented in the model are reservoir evaporation suppression by monomolecular film and destratification activities, phreatophyte control by spraying and mechanical clearing, and canal clearing and maintenance.

Objective Function Coefficients

The costs per acre of canal clearing of phreatophytes, the costs per acre foot of mechanical clearing and spraying of phreatophytes, and reservoir evaporation suppression are derived from Hughes et al. (1974, 1975), Culler (1970), Kearl and Brannan (1967), Bowser (1952), and Koogler (1952). The numbers used are given in Table 9.

The Water Consumptive Use Coefficients

Estimates of water consumptive use by phreatophytes were obtained from a Symposium on Phreatophytes sponsored by the American Geophysical Union and reported in *Transactions* (1952) and from Horton and Campbell (1974), Culler (1970), and Robinson (1958). The estimates of the amount of water that can be salvaged by the various evaporation suppression methods were derived in Hughes et al. (1974, 1975). Table 10 gives the maximum practical amounts of water salvaged by evaporation suppression and phreatophyte control.

Table 9. Estimated cost of water salvage alternatives.[a]

	Reservoir Suppression		Phreatophyte Suppression			
Subbasin	Monomolecular Film ($/AF)	Destratification ($/AF)	Sparse Growth Spraying ($/AF)	Dense Growth Spraying ($/AF)	Mechanical Clearing ($/AF)	Canal Lining ($/Acre)
1	9.20	10.00	10.00	35.00	20.00	1968.75
2	9.20	-	12.50	35.00	20.00	1968.75
3	9.20	5.00	9.25	22.50	15.00	1968.75
4	9.20	5.50	15.00	35.00	23.00	1968.75
5	9.20	-	12.50	25.00	17.50	1968.75
6	9.20	-	15.00	35.00	20.00	1968.75
7	9.20	3.00	9.20	20.00	15.00	1968.75
8	9.20	2.00	20.00	35.00	23.00	1968.75

[a] Missing numbers indicate that the alternative is not suitable in the subbasin.

Source: Hughes et al. (1974, 1975); Culler (1970); Kearl and Brannan (1967); Bowser (1952); and Koogler (1952).

Table 10. Estimates of water salvage from alternative methods (AF/yr).

	Reservoir Suppression		Phreatophyte Suppression			
Subbasin	Monomolecular Film	Destratification	Sparse Growth Spraying	Dense Growth Spraying	Mechanical Clearing	Canal Lining
1	1,312	1,500	5,000	1,500	5,000	24,000
2	1,165	0	5,000	2,000	5,000	23,400
3	5,723	8,395	12,000	28,000	15,000	66,000
4	1,117	6,800	5,000	2,000	2,000	53,200
5	1,117	0	5,000	10,000	10,000	109,000
6	256	0	5,000	2,000	5,000	5,200
7	3,236	5,250	15,000	5,000	15,000	18,300
8	1,965	140,200	2,000	3,000	2,000	16,400

Source: Hughes et al. (1974, 1975); Transactions, AGU (1952); Horton and Campbell (1974); Culler (1970); and Robinson (1958).

VI. MODEL RESULTS

Using the two-sector mixed-integer programming model to estimate the output of the agricultural and energy sectors and the impacts on water use of the adoption of water conservation measures, five future scenarios were analyzed. An initial baseline scenario (for the year 1974) was also analyzed to represent the present allocation of water. As the demand for water increases, the model recommends an economically optimal water conservation policy to water management policy planners in order to increase the economic welfare of the basin.

For Scenario I, the model maximizes net returns subject to water availability, capital, capacity, and other agricultural and energy inputs under projected conditions (years 1985 and 2000). The level of water quality is not constrained. Water is allocated between the agricultural and energy producing sectors until the values of the two marginal products (VMPs) of water are equal given the current market prices of inputs and outputs and without providing governmental regulatory or conservation programs. The value obtained for the net income of the basin economy is compared to the results achieved under the four alternate scenarios.

Scenario II maximizes net returns subject to maintaining water quality at the level specified by the 1974 EPA standards. This scenario allows for government regulation and investment in water conservation practices. Investments in water conservation technologies will decrease the amount of water used in energy and agricultural sectors.

Under Scenario III, the level of public investment in water conservation projects and in salinity control projects is assumed to be zero. The absence of public investment induces farmers to increase irrigation capital investment in order to conserve water in the agricultural sector and thus meet the salinity standards. Thus, this scenario gives higher investment levels in the private sector in the absence of government sponsored conservation measures to meet salinity standards. The difference in the objective values between Scenarios II and III represents the gains to society from government projects.

In the fourth scenario, downstream (Lower Basin) losses due to damages caused by increased levels of salinity are included in the model. The analysis determines if these losses are large enough to justify an increase in the level of investment in water conservation practices in the Upper Basin. The solution indicates the optimal salinity standard by equating marginal damage costs with the marginal salinity control costs which includes costs of some conservative techniques.

The fifth scenario also includes the salinity damage cost but with zero funding level of public investment. In the analysis, private investment increases until the marginal cost of private investment equals the marginal cost of damages due to increased salinity downstream from Lees Ferry.

Model Results for 1974

Table 11 compares the model results with the actual production levels for farm products. The predicted levels of water consumptive use for agriculture and energy production, by subbasin, are given in Table 12. The estimates predicted by this study compare favorably with estimates of other studies (see Narayanan and Bishop 1979; Padungchai 1980; Abbey 1979). The level of total water consumptive use generated by the model (approximately 2.02 million acre feet) is used as a base for comparing the water consumptive use in future years under alternative scenarios and water availabilities.

The model shows that for the base year 8.339 million tons of salt and 12.075 million acre-feet of water are delivered to the Lower Basin for an average of 0.69 tons of salt per acre foot. In comparison, the average historical flow of water at the compact point of Lees Ferry is 10,346 million acre feet with a load of 7.856 million tons of salt (according to water quality records) for an average of 0.76 tons of salt per acre foot.

1985 Model Results

By 1985, an additional 223,440 acres are projected to be irrigated and therefore, the land availability constraints were modified to include this

Table 11. Predicted and actual crop production in 1974 (acres).

Crop	Actual Production	Model Prediction	Deviation
Alfalfa hay	276,851	284,662	+7,811
Pasture and other hays	748,029	748,029	0
Small grains[a]	67,380	79,958	+12,578
Corn grain	18,635	14,760	-3,875
Corn silage	30,053	13,592	-16,461
Potatoes	3,093	3,040	-53
Total	1,144,041	1,144,041	0

[a] Small grains include barley, wheat, oats, rye, and sorghum for all purposes.

Table 12. Consumptive use of agricultural and energy production by subbasin in 1974 as predicted by the model (1,000 acre-feet).

Subbasin	Agriculture	Energy	Total
1	474.5	13.58	488.08
2	144.0	3.53	147.53
3	310.8	10.64	321.44
4	206.9	0.44	207.34
5	342.9	0.56	343.46
6	233.0	0.36	233.36
7	206.4	5.88	212.28
8	66.9	0.65	67.55
Total	1,985.4[a]	35.62[a]	2,020.98[a]

[a] The numbers do not add exactly due to rounding.

land in the right hand side values. In addition, the energy sector is expected to increase the capacities of some existing facilities and add several new facilities. Thus, the linear program model was used to determine the optimum water allocation and the appropriate adoption of water conservation measures by allowing the projected levels of additional agriculture and energy development expected in 1985 in the model.

Scenario I

By assuming that the agricultural and energy activities are optimized subject to the available water and water conservation technologies with no salinity standard enforced, the model determines a market water allocation without any consideration of externalities.

The estimated net returns to the agricultural and energy sectors show an increase of $1,677.7 million over 1974 levels (Table 13). The products of the agricultural sector and the comparison to the 1974 figures are given in Table 14. The 1985 water consumptive use associated with the increases in the agricultural and energy activities is 648,200 acre-feet more than the 1974 level. The associated water consumptive use by subbasin and the comparison to the use in 1974 is given in Table 15. The consumptive use of water by state is given in Table 16.

Private investment on 2,725 acres of sprinkler irrigated land in East Central Utah, West Central Colorado, and Southwestern Utah, at a total annual cost of $182,575 is adopted to maximize profits in the basin. No government sponsored conservation practice is adopted. The level of salt concentration downstream increases above the historical level of 0.76 tons of salt per acre foot by 9.5 percent.

The electricity sector used 100 percent wet tower cooling and the oil shale sector used surface mining in subbasin 2, Northwestern Colorado, and underground mining in subbasins 3 and 5, Northeastern Utah and Central Colorado. These technologies are based on profits and not on water consumption.

Scenario II

When public investment in water conservation and salinity control projects is undertaken to prevent the level of salinity concentration from exceeding the 1974 EPA standard, the net return to the Upper Basin decreases by $9.4 million. The solution requires $5.89 million investment in canal lining (2.68 miles) and sprinkler irrigation (9,083 acres). The investment in phreatophyte, evaporation and salinity control measures amounts to $2.60 million and salvages 224,000 acre-feet of water at an average annualized cost of $11.60 per acre foot. The total cost of these investments adds up to

Table 13. Estimated net returns to agriculture and energy in 1985 (millions of dollars).

Sector	Net Returns	Change from 1974
Agriculture	134.086	24.2
Energy	2,500.23	1,653.8
Total	2,634.13	1,677.7

Table 14. Production of irrigated land in 1985 by subbasin (acres).

Subbasin	Alfalfa	Pasture	Small Grains	Corn Grains	Corn Silage	Potato	Total	Change from 1974
1	39,161	277,231	23,789			4	340,185	0
2	30,676	70,516	6,908			14	108,114	14,400
3	71,506	95,047	16,468		8,938	11	191,970	25,240
4	34,036	82,969	6,807	4,255			128,067	11,300
5	71,801	102,925	14,360	8,975		108	198,170	9,000
6	76,526	38,053	15,305		9,566	2,613	142,063	45,500
7	116,624	66,633	25,979	14,578		178	223,992	118,000
8	14,097	14,655	4,293		1,762	112	34,920	0
Total	454,428	748,029	113,911	27,808	20,266	3,040	1,367,481	223,440
Change from 1974	169,766	0	33,954	13,048	6,673	0	223,440	

Table 15. Estimated water consumptive use in agriculture and energy in 1985 by subbasin (1,000 acre-feet).

Subbasin	Agriculture	Energy	Total	Change from 1974
1	474.5	39.2	513.7	25.6
2	158.6	51.1	209.7	62.2
3	360.3	47.3	407.6	86.2
4	228.9	1.96	230.86	23.5
5	360.4	15.3	375.7	32.3
6	351.1	0.4	351.5	118.1
7	427.3	61.1	488.4	276.1
8	67.0	24.8	91.7	24.2
Total	2,427.9	241.3	2,669.2	648.2

Table 16. Estimated water consumptive use by state in 1985 (1,000 acre-feet).

State	Total Allotment	Total Consumption	Unallocated Water
Wyoming	720	513.7	206.3
Colorado[a]	2,801	1,585.3	1,215.7
Utah	1,112	499.4	612.6
Total	4,633	2,598.4	2,034.6

[a] New Mexico's share of 0.695 MAF is included in Colorado's share.

$8.49 million. As a result, the water outflow to the Lower Basin increases, causing the concentration of salt to decrease 9.7 percent below the Scenario I level.

Thus, the model predicts that when the salinity constraint is relaxed (Scenario I), profits increase and no water conservation technologies are adopted. This suggests that the salt level, not water, is the major constraint to development in the Upper Colorado River Basin.

Table 17 shows the agricultural and energy consumptive use of water and the deviation of consumptive use over the initial 1985 solution.

Scenario III

When public investment for evaporation, phreatophyte, and salinity control projects is not provided, the net return to the Upper Basin decreases by over $13.30 million from the solution of Scenario I. The net return to the energy sector does not change, but the net agricultural income decreases by $5.9 million. The estimated costs of meeting the salinity standards account for the $7.40 million.

If only the salinity control projects are considered exclusive of evaporation and phreatophyte control projects, the total net return to the basin decreases by $11.4 million over Scenario I. The only salinity control project to be implemented is the Paradox Valley evaporation pond project at a cost of $1.64 million.

There are approximately 300 more miles of lined canals, 14,000 more sprinkler irrigated acres, and $1.05 million less total investment as compared to the solution given positive public investment (Scenario II). The energy sector does not adjust its water conservation technology in any industry. Table 18 shows the agricultural sector's consumptive use of water given zero investment in evaporation, phreatophyte, and salinity control projects.

Scenario IV

When the level of salt concentration is allowed to increase to the point where the marginal cost of salinity control is equal to the marginal damage downstream, the Upper Basin net returns are reduced by $3.5 million; yet, the basinwide returns increase by $500,000 as compared to the solution in which the

Table 17. Estimated water consumptive use in Scenario II in agriculture and energy in 1985 with the magnitude of reduction as compared to Scenario I (1,000 acre-feet).

Subbasin	Agriculture	Energy	Total	Deviation
1	474.5	39.2	513.7	0
2	158.1	51.1	209.2	-0.5
3	360.3	47.3	407.6	0
4	228.5	1.96	230.46	-0.4
5	290.5	15.3	305.8	-69.9
6	351.1	0.4	351.5	0
7	427.3	61.1	488.4	0
8	67.0	24.8	91.8	0
Total	2,357.4	241.3	2,598.7	-70.5

Table 18. Estimated water consumptive use in agriculture under conditions of government regulations and zero public investment in 1985 as compared to Scenario I (1,000 acre-feet).

Sub-basin	Agri-culture	Change
1	435.3	-39.2
2	158.1	-0.5
3	360.3	0
4	199.0	-29.9
5	292.8	67.6
6	351.1	0
7	310.6	-116.7
8	67.0	0
Total	2,174.2	-253.7

salinity level is regulated (Scenario II). The net returns to agriculture and energy do not change. The increase in salt concentration is 2.63 percent.

The cost of the salinity control and water conservation projects total $4.48 million and salvage over 229,000 acre-feet of water at an annualized cost of $19.51 per acre foot.

Scenario V

With no public investment in evaporation, phreatophyte, and salinity control projects, equating the marginal downstream damages with salinity control costs yields an increase in salt concentration of 6.6 percent over the EPA level and damages total approximately $8.66 million. Net basin profits decrease by $11.6 million over Scenario I and $2.7 million over Scenario IV. The net returns to agriculture and energy do not change.

Summary

Table 19 summarizes the cost and water salvage potential of various conservation measures and salinity control measures adopted under the four 1985 scenarios for 14.9 million acre-feet annual flow. The most efficient allocation of water is Scenario IV, which includes damage compensation estimates due to increased salinity downstream. As Table 19 indicates, the cost per acre foot of water conservation is $19.51 and the level of increased salt concentration is 2.63 percent over government specified regulations.

2000 Model Results

The same model is used to determine the net income to the basin for projected agricultural and energy development with the alternative water conservation measures induced by the policies represented in the various scenarios. An additional 9,360 irrigated acres are projected over 1985 estimates. Also, the energy sector is assumed to grow via the construction of new facilities (such as tar sand development, nuclear generation, and coal gasification) and the expansion of several existing facilities (such as electricity generation and oil shale production).

Scenario I

The net farm income of the region is predicted to be $134.4 million, a slight increase over the 1985 Scenario I; the net energy income is predicted to be $4,471.9 million, an increase of 80 percent over 1985. Within the agricultural sector, alfalfa production increases by 7,064 acres, small grains by 1,412 acres, corn for grain by 344 acres, and corn silage by 534 acres. The acreage increases predicted by the model occur in Northeastern and East Central Utah and in Central Colorado. The water consumptive use associated with the increases in the agricultural and energy activities is approximately 500,000 acre-feet more than the 1985 free market solution (Scenario I). Tables 20 and 21 show the consumptive use of water by subbasin and by state.

Table 19. Cost of water conservation technology and salinity control projects and the water salvaged under four alternative scenarios in 1985 under conditions of 14.9 MAF annual flows (cost in thousands of dollars).

Technology/ Project	Scenario II		Scenario III		Scenario IV		Scenario V	
	Salvage	Cost	Salvage	Cost	Salvage	Cost	Salvage	Cost
Agriculture								
Canal Lining	62,309	5,281.8 (2,683 miles)	65,821	5,872.8 (2,983 miles)	23,400	1,393.9 (708 miles)	23,400	1,393.9 (708 miles)
Sprinkler Irr.		608. (9,083 acres)		1,570.7 (28,453 acres)		608.5 (9,083 acres)		608.5 (9,083 acres)
Energy								
Other Sectors								
Res. Evap. Suppression	15,891	146.2			15,891	146.2		
Res. Destratification	162,145	390.5			162,145	390.5		
Spraying	42,000	242.0			32,000	299.0		
Mech. Clearing								
Salinity Control								
Paradox Valley	-4,000	1,638.0			-4,000	1,638.0		
TOTAL	278,345	8,489.0	65,821	7,443.5	229,436	4,476.1	23,400	2,002.4
(Cost/AF)	($30.50/AF)		($113.09/AF)		($19.51/AF)		($85.40/AF)	

The comparison of Tables 16 and 21 indicates that agricultural and energy consumptive use increases by 28,300 acre-feet in Wyoming, 199,200 acre-feet in Colorado and New Mexico combined, and 303,400 acre feet in Utah. The model predicts an increase in salt concentration over 1985 levels for Scenario I.

In the energy sector, wet tower cooling for both nuclear power and fossil fuel generation is used throughout the basin; surface mining of oil shale is used in Northwestern Colorado while underground mining is used in Southwestern Wyoming, Northeastern Utah, and Central Colorado; surface retorting of tar sands for oil is implemented in Colorado and in Northeastern, Central, and Southwestern Utah; and the lurgi method of coal gasification is used in Wyoming and Utah. The energy sector impacts are the same for all scenarios for the year 2000.

Scenario II

The net return to the Upper Basin decreases by $13.35 million when a salinity standard is imposed. The net return to agriculture decreases by $4.2 million. Salt loading is decreased and the Colorado River outflow to the Lower Basin increases by 500,000 acre-feet. As for 1985, salinity control is shown to be more restrictive toward agricultural development than are limitations in available water.

Table 20. Estimated water consumptive use in agriculture and energy in 2000 by subbasin (1,000 acre-feet)

Subbasin	Agriculture	Energy	Total
1	451.6	90.4	542.0
2	158.1	106.1	264.2
3	368.7	332.4	701.1
4	228.5	4.7	233.2
5	367.6	26.8	294.4
6	354.6	0.7	355.3
7	427.3	109.9	537.2
8	67.0	34.7	101.7
Total	2,424.2	705.7	3,129.9

Table 21. Estimated water consumptive use by state in 2000 (1,000 acre-feet).

State	Total Allotment	Total Consumption	Unallocated Water
Wyoming	542.0	542.0	0
Colorado[a]	2,171.0	1,785.1	931.9
Utah	1,100.0	802.8	297.2
Total	4,359.0	3,029.9	1,229.1

[a] New Mexico's share of 0.695 MAF is included in Colorado's share.

The public investment in water conservation projects totals $9.1 million for lining canals, using sprinkler irrigation, suppressing evaporation, and phreatophyte spraying. The public investment in salinity control is $1.6 million for the Paradox Valley evaporation ponds. Over 281,000 acre-feet of water is salvaged, thus reducing the salt concentration downstream.

Scenario III

The net return to the basin decreases an additional $4.7 million under the condition of zero expenditures for public investment to control water evaporation, phreatophytes, and salinity. The total investment costs increase by $3,757,100 (41 percent). Over 147,000 acre-feet of water is salvaged.

Table 22 shows the agricultural consumptive use of water given the Scenario III assumptions of zero public investment in evaporation, salinity, and phreatophyte control projects with salinity regulation. As compared to the "no salinity regulation" results of Scenario I, there is a 237.0 acre-feet decrease in consumptive use.

If the salinity control projects are funded while evaporation and phreatophyte control are not, the total net return to the basin decreases by $15.7 million over Scenario I (as compared to a $18 million decrease without salinity control funding). The only salinity control project to be funded is the Paradox Valley unit and the length of canals that are lined decreases by 2,000 miles.

Scenario IV

Net sector returns decrease by $12.2 million when downstream damages are included in the objective function. The total increase in salt concentration over the EPA level set in 1974 is 5.03 percent with an associated damage cost estimated to be over $6.7 million.

The total cost of water conservation projects and salinity control projects is over $4.55 million, salvaging 229,000 acre-feet of water at $19.85 per acre foot. The water conservation measures include canal lining, sprinkler irrigation, reservoir evaporation suppression, phreatophyte control, and salinity control investment in the Paradox Valley unit.

Table 22. Estimated water consumptive use in agriculture under conditions of a salinity regulation and zero conservation investment in 2000 with the magnitude of change as compared to no salinity regulation (1,000 acre-feet).

Subbasin	Agriculture	Change
1	453.3	-16.3
2	158.1	0
3	368.7	0
4	195.5	-33.0
5	297.4	-70.2
6	354.6	0
7	310.6	-116.7
8	67.0	0
Total	2,187.2	-237.0

Scenario V

The net returns to the basin decrease an additional $1.2 million as funds for reservoir evaporation suppression, phreatophyte control and salinity control projects are eliminated. The elimination of the $2.5 million of public investment also increases the salinity level of the Colorado River from 5.03 percent to 8.86 percent, with an associated increase of $5.2 million in damage costs.

Summary

Table 23 summarizes the cost and water salvage potential of various conservation measures and salinity control projects under the four scenarios in 2000 for 14.9 MAF annual flow.

Scenario IV is the most efficient allocation of water given public investment. The cost of water conservation per acre foot of water salvaged is $19.85. A total construction expenditure of $4.5 M reduces damage costs by $6.7 million.

Overview of Research Results

A mixed-integer programming model is used to determine 1) the optimal level of public investments in water conservation programs, 2) the level of expenditures required in alternative conservation activities in each subbasin, and 3) the changes in the investment requirements over time in the Upper Colorado River Basin. The objective function for the programming model consisted of four components. These are 1) the value of agricultural output, 2) the value of the energy sector output, 3) the cost of public programs in water conservation as well as salinity reduction, and 4) the salinity damage costs for the Lower Basin. The first two components represent benefits and the last two components are costs which are subtracted from the sum of the first two.

The model was solved for the base year 1974 and two future years 1985 and 2000 under increased water demand conditions. Solutions for each of the two future years 1985 and 2000 were obtained for five alternate scenarios.

In the first scenario, the value of agricultural and energy outputs are maximized net of water conservation costs. The externality due to changes in salt concentrations are not taken into account. The second and third scenarios are designed to determine the cost of meeting the salinity standards specified by EPA with and without government investments. The fourth and fifth scenarios internalize the externality and determine the efficient salinity standard with and without government investments. The five scenario analyses were performed for demand conditions for years 1985 and 2000. The results of these analyses are summarized in Table 24.

From the results of Scenario I, it is apparent that when salinity changes are not regulated or the externality is not internalized, public investments in water conservation programs are not economically efficient since the marginal value of water in the Upper Basin is less than the cost of water saved through implementation of conservation programs. However, this conclusion changes as soon as regulatory measures are introduced or externality is internalized. To evaluate these alternate scenarios and make comparisons between them, the following graphical analysis will be useful.

In Figure 3, the horizontal axis measures the percent of salinity reduction from levels indicated under Scenario I. In the vertical axis, marginal benefits and costs of salinity reductions are measured. The marginal benefit curve A represents the additional benefits the Lower Basin will receive as a result of improved water quality (reduction in salinity by a percent). B represents the marginal

Table 23. Cost of water conservation technology and salinity control projects and the water salvaged under four alternative scenarios in 2000 under conditions of 14.9 MAF flow (cost in thousands of dollars).

Technology/ Project	Scenario II		Scenario III		Scenario IV		Scenario V	
	Salvage	Cost	Salvage	Cost	Salvage	Cost	Salvage	Cost
Agriculture								
Canal Lining	65,821	5,872.8 (2,983 miles)	147,003	11,115.0 (5,646 miles)	23,400	1,393.9 (708 miles)	23,400	1,393.9 (708 miles)
Sprinkler Irr.		631.9 (9,432 acres)		1,691.5 (24,351 acres)		631.9 (9,432 acres)		631.9 (9,432 acres)
Energy								
Other Sectors								
Res. Evap. Suppression	15,891	146.2			15,891	146.2		
Res. Destratification	162,145	390.5			162,145	390.5		
Spraying	42,000	424.0			32,000	299.0		
Mech. Clearing								
Salinity Control								
Paradox Valley	-4,000	1,638.0			-4,000	1,638.0		
TOTAL	281,857	9,103.4	147,003	12,806.5	229,436	4,499.5	23,400	2,025.8
(Cost/AF)	($32.30/AF)		($87.48/AF)		($19.85/AF)		($88.88/AF)	

Table 24. Summary of benefits and costs (in millions of dollars).

Solution Year Scenario #	Value of Agri-cultural Output	Value of Energy Output	Cost of Private Conservation	Cost of Government Conserva-tion Programs	Changes in Lower Basin Damage Costs (Changes in Salinity)	Net Benefits
1974 Scenario 1	109.90	846.43	-	-	0	956.33
1985 Scenario 1	134.09	2500.23	0.18	-	-12.71 (9.5%)	2621.42
2	133.17	2500.23	0.18	8.49	0 (0%)	2624.73
3	128.19	2500.23	0.18	7.44	0 (0%)	2620.80
4	133.17	2500.23	0.18	4.48	-3.52 (2.63%)	2625.23
5	133.17	2500.23	0.18	2.00	-8.66 (6.46%)	2622.56
2000 Scenario 1	134.44	4471.87	0.18	-	-16.05 (12%)	4590.08
2	130.20	4471.87	0.18	9.11	0 (0%)	4592.78
3	129.18	4471.87	0.18	12.81	0 (0%)	4588.12
4	133.49	4471.87	0.18	4.50	-6.73 (5.03%)	4593.95
5	133.49	4471.87	0.18	2.03	-11.85 (8.86%)	4591.29

cost of reducing salinity by alternate techniques. Some of the techniques include conservation measures that reduce salinity through dilution. C represents the marginal cost of reducing salinity without any public investments in conservation. Since some of the lower cost alternatives are eliminated in the latter case, the marginal cost (curve C) of reducing salinity is higher than the marginal cost of salinity control when all alternatives are available.

Under Scenario I for the year 1985, increase in salinity is estimated to be 9.5 percent from 1974 levels (Table 24). In Scenario II, the salinity level is reduced by 9.5 percent by alternative techniques. In Scenario III, the same reduction is obtained without any government investments. Under salinity regulations, the cost of reducing salinity without government investments is given by the area EFX_3X_2. This is equal to \$3.93 million (Table 24). When externality is internalized (Scenario

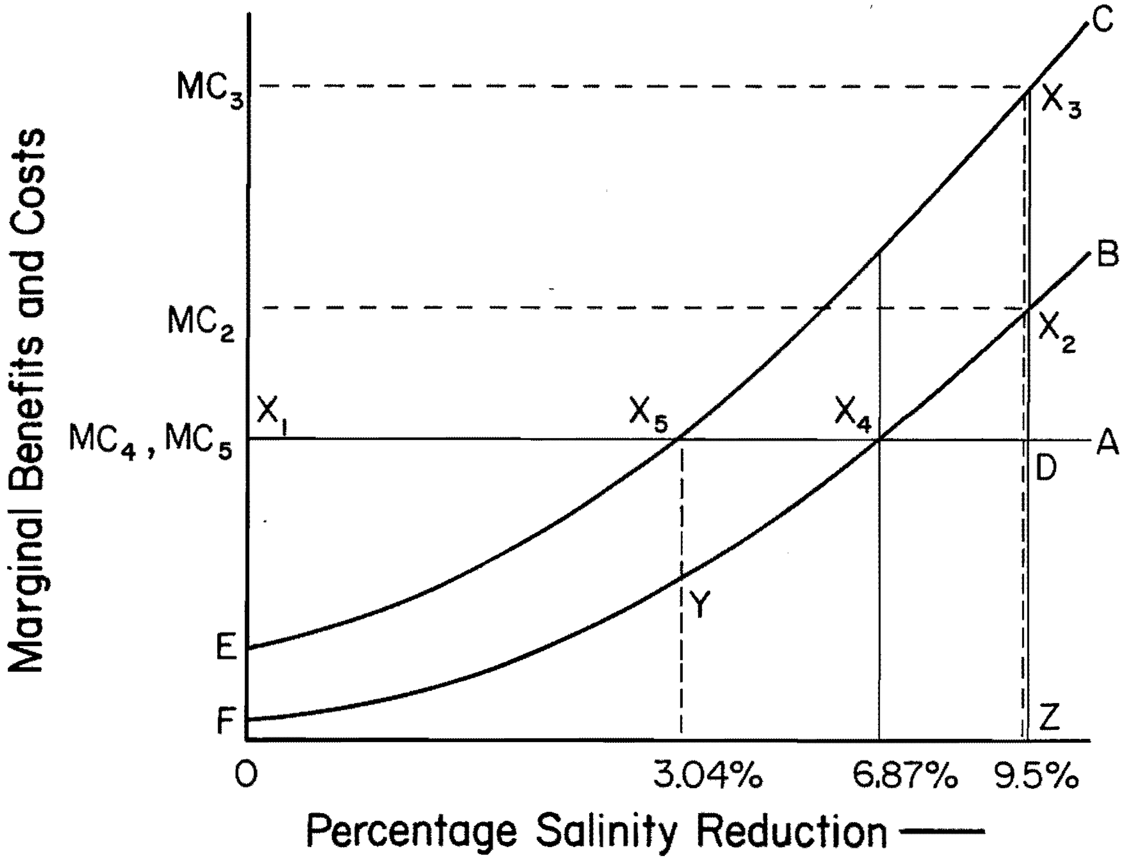

Figure 3. Percent of salinity reduction and marginal benefits and costs of salinity reduction.

Table 25. Cost of salinity control policies and benefits of conservation program (million dollars).

Year	No Salinity Regulations	Salinity Level Set By EPA Regulation			Salinity Level Determined by Marginal Benefit = Marginal Cost		
		With Government Investment	Without Government Investments	Benefits of Government Programs	With Government Investment	Without Government Investments	Benefits of Government Programs
1985	3.81	0.5	4.43	3.93	0	2.67	2.67
2000	3.87	1.17	5.83	4.66	0	2.66	2.66
Areas in Figure 3	X_1X_4F	X_4X_2D	FX_4DX_3E	FX_2X_3E	-	$EFYX_4X_5$	

IV), the optimal solution requires that salinity levels be reduced by 5.87 percent from 1974 levels. This gives the maximum net benefits of $2625.23 million. Under this solution the Lower Basin incurs a damage cost of $3.52 million. The cost of achieving this solution without government investments is $2.67 million. The corresponding salinity reduction required is where the marginal benefit A and marginal cost C intersect at 2.04 percent. Comparing the effect of proposed regulatory standards with the solutions that internalize the externality (comparisons of 2 and 4, 3 and 5) indicate that the cost of proposed EPA regulation involves $0.5 million and $1.76 million respectively. The results are summarized for years 1985 and 2000 in Table 25.

VII. CONCLUSIONS

The model results indicate that government-sponsored water conservation measures are not needed to supply present and projected water demands in the Upper Basin. However, for meeting the EPA specified salinity levels, water conservation becomes feasible. Comparing the solutions with and without government investments in water conservation measures in the presence of salinity standards (Scenarios II and III), society could gain $3.9 M dollars annually in 1985 and $4.7 M by 2000 by investing in conservation measures. However, the marginal cost of expanding the salinity control program to the level required to meet the salinity standards is greater than the marginal reduction in salinity damages to the Lower Basin (estimated at $250,000/mg/liter in 1974 dollars). If this damage cost is included in the objective function, marginal costs are reduced to meet the marginal benefits and the optimal amount of water conservation is less than that for Scenario II. The cost of salinity regulation is minimized under Scenario IV, and basinwide gains result. The optimal salinity levels estimated by using Scenario IV indicate that the salinity standard should be relaxed by 2.6 and 5 percent from 1974 levels at Lees Ferry for economic efficiency in years 1985 and 2000 respectively.

The value of water conservation seems to be in reducing salinity levels downstream. Except for the salinity problem, implementation of conservation methods is not economically viable. In order to check the sensitivity of this conclusion to variability in water supply, model solutions were also obtained for a smaller annual water availability of 13.8 MAF. The results are not significantly different.

As one more test, since the salt contributions by irrigated agriculture are predominantly in the growing season, a 6-month seasonal model was also constructed. The model solutions indicate that the salinity problems are less severe than the results of the annual models indicate. Consequently, the required investments in conservation are also correspondingly smaller. This result follows from the following reasoning. In the growing season, the percentage of salt pick-up due to irrigation increases relatively more than the average in the annual model. However, the percentage increase in flow in the growing season relative to the increase in salt pick-up is greater and therefore, the severity in changes in the salt concentrations is smaller. This explains why the investments required for conservation are also smaller.

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