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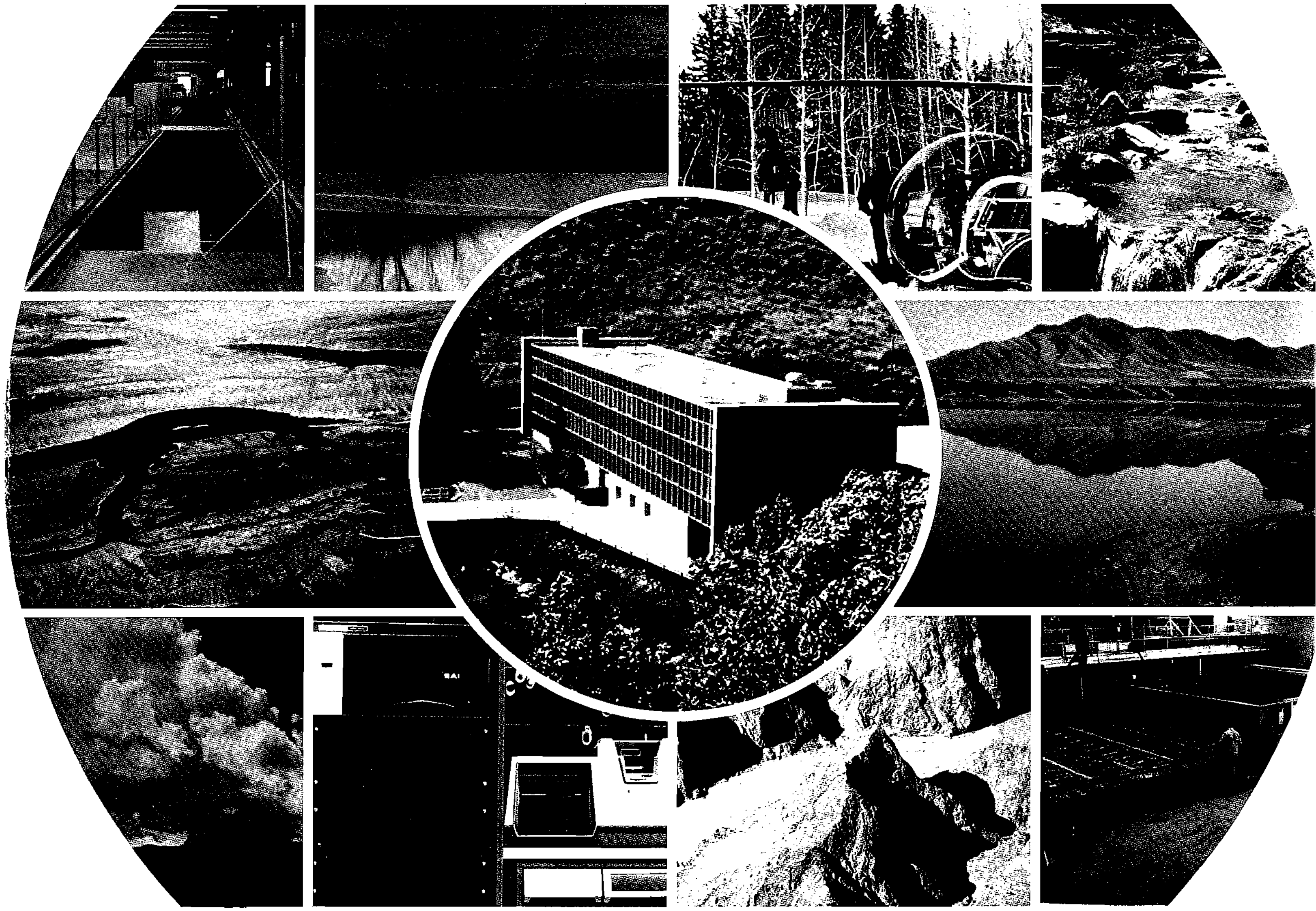

Utah Water Research Laboratory
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WATER RESOURCES PLANNING SERIES
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AN ECONOMIC EVALUATION OF THE SALINITY IMPACTS FROM ENERGY DEVELOPMENT: THE CASE OF THE UPPER COLORADO RIVER BASIN

by

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ABSTRACT

To analyze the effect of potential energy development on water allocation and water quality in the Upper Colorado River Basin, a linear programming model is formulated. Using the model, changes in salinity are predicted. Further, least-cost strategies to maintain the established numeric salinity criteria through both structural and nonstructural alternatives are developed. The effectiveness of alternative control measures are examined within given institutional constraints. Based on cost-benefit analysis, optimal salinity levels over time are proposed. The economic feasibility of presently planned structural measures to reduce salinity is investigated and contrasted with nonstructural alternatives.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF TABLES (CONTINUED)

I. INTRODUCTION

Present national energy policies emphasize reduction of U. S. dependence on imported energy through higher rates of domestic production. Strong economic incentives and rising energy prices will stimulate through increased profitability the development of domestic energy resources. In the western states, the Upper Colorado River Basin, with its vast deposits of coal, oil, natural gas, uranium, tar sands, and oil shale, is consequently faced with large-scale development.

Water is required for development of these energy resources. It is necessary for all aspects of energy production, including mining, reclamation of mined lands, processing, refining, conversion, and distribution. In addition, water will be needed for the associated growth of population, commercial and service sectors, and for the development of other industries in the region. Thus, the increased production of energy resources is expected to increase the demand for water substantially.

Concern as to whether the needed water will be available to sustain energy development and associated economic activities has stimulated a number of "water for energy" studies for the western states. Studies to date (U. S. Bureau of Reclamation 1974a, Davis and Wood 1974, Utah Division of Water Resources 1973, Federal Energy Administration 1974, U. S. Department of the Interior 1974, U. S. Water Resources Council 1974, and Western States Water Council 1974) have taken an inventory approach, itemizing proposed energy projects and determining the availability of water to meet the estimated needs. The general conclusion with regard to water availability in the Upper Colorado River Basin (U. S. Department of the Interior 1974) is, according to available data,

> ...the water supply exceeds that which is presently being utilized in the Basin. However it is also apparent that the supply is in turn exceeded by the presently recognized rights to utilize water which has been granted by most of the states in the Basin.

Therefore, the availability of water for the production of energy and to supply the needs of associated users will depend on the ability of the energy industries and associated users to acquire the necessary water rights through various transfer mechanisms. Small quantities of water may be as yet uncommitted and can be obtained through legal appropriation procedures. Water that has already been appropriated by others will have to be purchased for energy uses. To the extent that economic considerations govern this transfer, the purchases will come from existing uses where the marginal product of water is relatively low.

Various institutional constraints may shift the transfer to uses with higher marginal products. For example, complications may arise in acquiring water held by the federal government and native American Tribes. Additional legal and institutional constraints are found in interstate and intrastate obligations, Upper-Lower Basin compacts, and U. S.-Mexican treaties. These have to be regarded as social property rights to which any reallocation schemes should conform. The free market system, as a vehicle to promote intersectoral mobility of water under these institutional restraints, promotes economic efficiency if there are no third-party effects.

However, the pattern of water allocation may have an important third-party effect by impacting water quality of the Colorado River. Higher consumptive use of the presently unutilized water upstream on the one hand, can increase concentrations of certain constituents through reduction in streamflow and consequent dilution possibilities. On the other hand, changes in the water use, as well as wastewater management of the users, may alter waste loading in the river giving rise to water quality changes.

Salinity is recognized as one of the major problems of the Colorado River. Although salinity does not cause major damage to water users in the Upper Colorado River Basin, the high total dissolved solid (TDS) levels in the river impose significant damages on the industrial, municipal, and agricultural users in the Lower Basin. Higher salinity levels in irrigation water cause crop damage, reduction of soil productivity, and increased demand for water for leaching. In municipal and industrial uses, salinity causes higher treatment costs, pipe erosion and scaling, and greater use of detergents and chemicals. The total damage in the Lower Basin caused by increases in salinity level that have already occurred is estimated to be $53 million per year and is likely to increase to $124 million per year by 2000 if no salinity control measures are taken (U. S. Department of the Interior 1977). Federal and state governments are actively involved in the Upper as well as portions of the Lower Basin to control salinity levels in the river. The Environmental Protection Agency, the Bureau of Reclamation, the Soil Conservation Service, state Water Resources Divisions, and Health Divisions are carrying out various programs and proposing others for the future. The effectiveness of the proposed measures needs to be investigated through comparison of available alternatives in the context of the effort required, as partially determined by the amount of energy development. Some preliminary studies to assess the energy development impacts on water quality have used simulation approaches (Utah State University 1975, Andersen and Keith 1977, Bishop 1977). The results indicate that energy development is likely to increase salinity loading. An integrated framework of economic analysis is needed to better define the water quality changes and the consequent environmental externalities that can be expected to result from water reallocation due to energy development.

In summary, prospective energy development in the Upper Colorado River Basin is expected to increase the demand for water substantially. The resulting shift to higher valued uses is expected to increase downstream salinity levels and consequent lower basin damages. With the amendment of the Colorado River System Implementation Plan (Section 120.5 to 40 CFR Part 120), numeric criteria (target concentrations) for salinity have been established. Several measures to maintain or lower present salinity levels are being pursued under the Colorado River Salinity Program authorized by PL 93-320. However, no known quantitative assessment has been made to evaluate whether the 1972 salinity levels are "optimal" in any economic sense. Also, the cost of control has not been compared with the benefits of reduced salinity to the proposed concentration standards.

Consequently, present standards cannot yet be defended on economic efficiency or distributional grounds. Further, the planned measures to control TDS levels are aimed only at reducing salt loading from natural and man-induced activities. Management to reduce the concentrating effects of additional consumptive uses upstream is disregarded as a control alternative. In fact, the proposed regulations explicitly allow full development of the compact-apportioned water in the Upper Basin while maintaining salinity levels in the lower main stream at 1972 levels.

One good aspect of the salinity regulations is that they provide for review of the standards at 3-year intervals. If future water allocations and salinity control measures are appropriately planned using economic criteria, the cost of controlling salinity can be minimized as salinity concentrations with maximum social benefits are established.

The objectives of this research are to a) assess the impact of energy development in the Upper Basin on salinity of the Colorado River; b) evaluate the costs of compliance with established numeric salinity concentration criteria using proposed salinity control measures; c) compare (b) with minimum cost alternatives to comply with salinity standards by explicitly investigating water reallocation and possible salinity reduction through dilution; d) determine socially optimal salinity standards and compare costs and benefits associated with (b) and (c); e) recommend policies based on this analysis for future planning and implementation of Upper Basin water allocation and salinity control.

In order to accomplish these objectives, relevant economic analysis is developed in the next section, and criteria based on economic efficiency are derived. A physical description of the case study area, legal and institutional aspects of water resources and quality, and the economic activities of the region are outlined in the third section. An operational procedure to accomplish the stated objectives, based on a mathematical optimization model, is developed in the following section. The data needed to solve the problem are developed in the next section. In the final section, results of the study and their policy implications are discussed.

II. ECONOMIC ANALYSIS

This section presents a framework for economic analysis that can be applied to resolve the water quality issues arising from energy development possibilities in the Upper Colorado River Basin. The method explicitly examines the effect of water reallocation in the basin in order to provide criteria for selecting the minimum cost combination of measures for maintaining any desired salinity standards. Rules for achieving optimal salinity levels are outlined based on cost-benefit analysis.

Externalities from Water Pollution

Deterioration of water quality is a nationwide problem in the United States. Public Law 92-500, the Federal Water Pollution Control Act Amendment of 1972, is evidence of the public's growing awareness of water quality problems. Water pollution reduces the productivity of water and hence imposes higher costs on downstream users. It is a classic example of a technological external diseconomy. When Pareto relevant technological externalities exist, misallocation of resources will result.

Controlling waste discharges (or residuals) has been the major strategy for improving water quality, but it is not the only available alternative. Pollution damages are a function of concentration rather than just the total amount of wastes discharged. Total dissolved solids (TDS) or salinity per unit of water may be reduced either by reducing discharges or increasing flows. Additional upstream water depletions may have detrimental effect on downstream water quality. Water allocations to upstream users will not be optimal if damages to downstream users resulting from upstream water depletion are not taken into consideration. Furthermore, improving water quality by controlling waste discharges alone will result in a nonoptimal solution. Perhaps because of the traditional separation between water supply planning and water quality management in the United States, none of the policies evaluated for salinity control have explicitly studied reducing both upstream water use and waste discharges simultaneously. Procedures for integrating applications of economic criteria to both situations are needed to guide the allocation of water resources to achieve the socially optimal solution.

Literature Review

Technological externalities cause divergence between social and private welfare. In his classic work on how to remedy this situation, Pigou (1932) proposed a tax and subsidy (bounty) scheme to correct externalities. The scheme would levy a tax on parties imposing external diseconomies and pay a subsidy to damaged parties. Coase (1960), Buchanan and Stubblebine (1962), and Turvey (1963) argued that taxes and subsidies are unnecessary if two parties voluntarily negotiate for their mutual advantages. The voluntary approach has been criticized strongly in its assumptions and application to the real world (Arrow 1969, Dolbear 1967, and Dick 1976). Pigouvian tax and subsidy systems are costly and difficult to apply when externalities involve large groups of polluters and pollutees. To avoid the difficulty of using the Pigouvian tax alone as an instrument for controlling pollution, Baumol and Oates (1971) suggested it be used to achieve preselected environmental quality levels. They claimed that a uniform tax would require less information.

Hass (1970) utilized the Dantzig-Wolfe decomposition algorithm to find the optimal treatment configuration for meeting water quality standards for the Miami River of Ohio. Simultaneously, optimal pollution taxes to achieve this configuration were determined without complete knowledge of treatment cost functions. Upton (1968) derived a method for determining the level of pollution taxes that would raise revenue sufficient to pay for the cost of the low flow augmentation method. The effectiveness of using economic incentives by decentralized and centralized approaches to improve water quality were discussed and compared (Kneese and Bower 1968, Johnson 1969). The importance of the concentration level rather than the quantity of wastes discharged to the environment was pointed out by Tietenberg (1974). He proposed a zonal tax system which utilized uniform tax rates within zones but varies across zones.

None of the previous studies has combined policies influencing both water depletion and waste discharges. Since economic damages to downstream users result from both total salinity discharge and upstream water consumption, attempts to solve the problem by dealing with only one of these two variables are in general economically inefficient. Controlling salinity by reducing waste discharges has been discussed and low-flow augmentation and desalting alternatives need to be integrated into the analysis.

Economic Implications of Dilution

To illustrate this point, two groups of water users will be assumed in a river basin. Allocation of a given quantity of water by maximizing combined profits for the two users is economically efficient. In the absence of externalities, market mechanisms will lead to optimal allocations. When externalities resulting from water pollution are present, voluntary transfer of consumptive use portions of water rights will no longer result in optimal allocation.

The two user groups, firms 1 and 2, use water as an input in their production processes. Firm 1 discharges salt load in proportion to the amount of water used. No salt is discharged by firm 2. Line $W_0 W_0$ represents the maximum quantity of water available for use by the two firms (Figure 1). The slope of $W_0 W_0$ reflects the ratio of the marginal value of water to firms 1 and 2. Firms 1 and 2 are price takers in input and output markets. Let π_1 be an isoprofit curve whose properties are derived in Appendix A. Every point on π_1 represents a combination of water used in firm 1 (W_1) and water used in firm 2 (W_2) that yields a specified level of joint profits. The slope of the tangent at a point on an isoprofit is the ratio of the marginal profit of firm 1 to marginal profit of firm 2 from using water in their production. If water is assumed to be fixed in supply, the marginal profit of each firm is the value of the marginal product of water to that firm. The highest combined profits of firms 1 and 2 depend on the availability of water and its marginal productivity. Any combination of W_1 and W_2 cannot exceed the available quantity $W_0 W_0$ Therefore, $W_0 W_0$ is the resource constraint. The tangency of π_1 and $W_0 W_0$ shows the optimal allocation of resources under free trade. At A, the point of tangency, firm 1 consumes OW_1^o units of water, and firm 2 consumes OW_2^o. The sum of the highest net profits attainable by the firms is π_1. The quantities OW_1^o and OW_2^o are the optimal allocation of water resources from the private point of view. If the amount of water used, OW_1^o plus OW_2^o, imposes substantial economic losses on downstream water users, the river basin authorities may desire to maintain a higher level of water quality to reduce downstream damages.

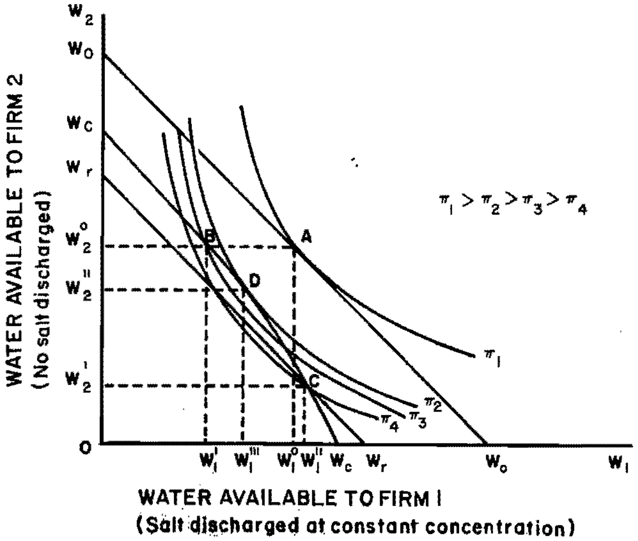

Figure 1. Allocation of water under quantity and quality constraints.

Line $W_c W_c$ is the boundary of a maximum allocation of W_1 and W_2 which meets a certain quality standard, C^*. The properties of $W_c W_c$ are derived in Appendix B. The joint profits π_1, are no longer attainable since consumption of OW_1^o and OW_2^o by firms 1 and 2 will violate standard C^*.

If the river basin authority dealt with the problem only by reducing waste discharges, it would reduce water use by firm 1 from OW_1^o to OW_1' but the amount of water used by firm 2 (OW_2^o) would be unaffected. The joint profits would be π_3. The allocation of water at B, however, is nonoptimal because the slope of π_3 curve is steeper than the slope of the curve $W_c W_c$. The ratio of the value of the marginal product of an additional unit of water to firm 1 (VMP_1) to firm 2 (VMP_2) is greater than the marginal rate of substitution in concentration of W_1 for W_2 ($\frac{\partial C}{\partial W_1} / \frac{\partial C}{\partial W_2}$). This can be interpreted as firm 1's sacrifice of marginal profit from water use being greater than firm 2's. Firm 1 will experience a reduction in its profit.

On the other hand, if the authorities choose to deal with the problem by reducing water use, both firms 1 and 2 must decrease their production. If it were decided to reduce total water use to that represented by line $W_r W_r$, the maximum joint profits attainable to the two firms fall from π_1 to π_4. At C where $W_r W_r$ passes through $W_c W_c$ and the π_4 curve, the allocation of water OW_1'' to firm 1 and OW_2' to firm 2 is also nonoptimal. Thus, reducing the amount of water supplied to users in a basin is also an inefficient method for improving water quality.

Since controlling either one of the two variables alone is economically inefficient, policies to deal jointly with the two control variables should be devised. The optimal policy must involve both reducing salt loading and reducing the volume of water consumption upstream. Only the allocation at point D where the joint profits curve π_2 is tangent to the water quality standard curve $W_c W_c$ is optimal. This implies an equality in the rates of sacrificing water by firms 1 and 2 to maintain water quality. Firm 1 will use water OW_1'' units and firm 2, OW_2'' units. The joint profit, π_2 is the highest profit that firms 1 and 2 can obtain under the water quality restriction.

Policy Alternatives for Water Pollution Control

The above analysis indicates that measures aimed at reducing the salt load should be combined with water allocation adjustments to reduce salinity levels downstream. Implementation of economic incentive systems such as tax-subsidy schemes (Kneese and Bower 1968, Baumol and Oats 1971) that deal with only one of the two factors may not be effective in this case. The needed incentive system is one applicable to water used and the amount of wastes discharged. The optimal ratio of taxes or subsidies (following Pigouvian tradition) to water use and salt discharge is equal to the slope of $W_c W_c$ at D. The magnitude of the taxes and the ratio must be determined iteratively. Line $W_c W_c$ needs to be derived through a water quality model.

Further, if the supply of water is inelastic for upstream users, tax on water will not affect the consumption upstream. Unless upstream-downstream water mobility is permitted, the tax subsidy scheme will not achieve the purpose of maintaining the "desired" quality at least cost. The tax revenue from water will simply be a part of the rent accruing to the owner of water rights; therefore, maintenance of water quality will be achieved only through reduction in salt discharge.

Planning procedures are needed to resolve the issue. It is well recognized that water quality should be treated as a basin-wide problem for salinity control purposes. Yet, the relationships between institutions involved with water allocation decisions and those with water quality management are not clearly defined and their activities are certainly not integrated. Consequently, water resource development is likely to proceed independently of salinity considerations. The need for coordination of state water rights and water resources divisions with EPA and state health divisions is clear. Further, concerted efforts by these organizations to make future decisions based on basin-wide economic planning models are needed.

Aside from efforts to reduce salinity concentration through reduced upstream water use and reduced salt loading from human activities, the role of natural salt contribution to the river system (which is estimated at about 60 percent in the Colorado River) must be examined. Salinity control through economic incentives will fail in this area since alternatives to remove natural salt inflows are public goods. Consequently, if the costs associated with reducing loadings from natural salt sources are lower than the other options, efforts to incorporate these possibilities in the planning procedure deserve attention. Indeed, such plans are being pursued by the Bureau of Reclamation under Section 206 of Title II of the Colorado River Basin Salinity Control Program Act (PL 93-320). The effect of individual structural alternatives has been analyzed through simulation models (U.S. Department of the Interior 1977) in a cost-effectiveness framework.

Optimal Water Quality Level

To date, these three alternatives (control of salt loading from human activities, control of natural salt loading, and reductions in water use) have not been evaluated in a comprehensive analytical framework to determine the combination that would maintain salinity levels downstream at least cost. The economic criteria for achieving any "desired" water quality level downstream dictate that the level of each salinity control technique should be so chosen that the quality improvement achievable by expending an additional dollar for each control measure be the same. This condition will yield the cost-minimizing combination of techniques.

The analysis simultaneously needs to determine the level of salinity that is economically optimal. In Figure 2, the curve sloping downward to the right (MB) represents the marginal benefits to downstream users as a function of improvement in water quality. The area under the curve is the total benefit resulting from the water quality improvement. The shape of the curve indicates that benefits increase at a decreasing rate as salinity levels are reduced. Curve MC represents the marginal cost of improving salinity. It is the slope of the minimum total cost of

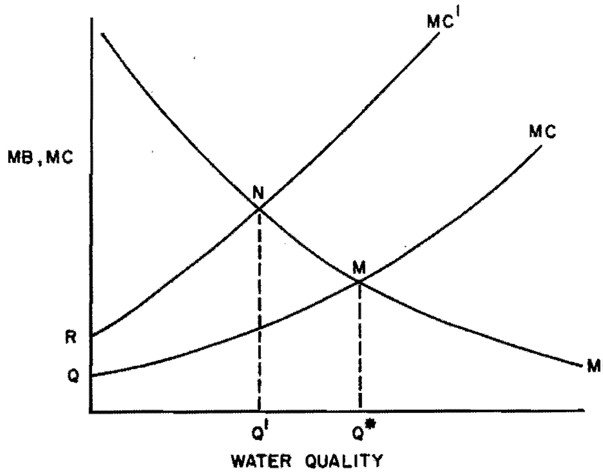

Figure 2. Optimal water quality level.

achieving given salinity levels through combinations of alternative salinity control measures. The maximum social benefit will be realized at point M where marginal benefits equal marginal costs.

The quality level Q* is the economically efficient level. At this level, the additional cost of improving water quality by one unit equals the additional benefit to the downstream users from that incremental improvement. If some available salinity control measures are not considered, then the cost of achieving any desired level will be greater than the minimum cost alternatives. In such a case, the marginal cost MC' will be higher than MC. Correspondingly, the "optimal" water quality suggested by this rule Q' will be lower than Q*.

The economic criteria developed in this section will be applied to resolve the salinity issue in the Colorado River Basin, particularly in the face of projected energy development in the area. An operational model will be structured in a planning context, and the results will be compared to the on-going and planned salinity control measures in the basin to determine the effectiveness of alternative plans under the economic criteria. Numerical results derived from this model can be used for future planning for energy development in the basin.

III. WATER RESOURCES OF THE UPPER COLORADO BASIN

Development of the abundant energy resources of the Upper Colorado River Basin is going to require substantial amounts of water. The necessary water will largely have to be obtained from previous users, and the transfer will have to be accomplished in a manner that does not appreciably worsen salinity for Lower Basin and Mexican users. In order to determine how the reallocation can best be achieved within this constraint, information is needed on water availability, water quality, present and planned water use, developmental plans, and institutional situations affecting water resources and water quality management in the basin.

The 1440-mile long Colorado River drains portions of seven states before flowing into Mexico. It produces less water per unit area (60 acre feet annually per square mile) than any other drainage in the country. One reason is that high mountain watersheds in a relatively small percentage of the total Upper Basin provide almost the entire source for the water needed to support irrigated agriculture, municipal water supply, industry, mining, wildlife, and recreation.

The Colorado River Basin is divided for interstate water allocation purposes into an Upper and Lower Basin, the dividing point being Lee Ferry, Arizona, below Glen Canyon Dam. The Upper Basin states include Wyoming, Colorado, Utah, and New Mexico (Figure 3). The laws through which the limited amounts of available water are allocated among the many competing uses in this arid climate encompass a multitude of complex legal and institutional arrangements which are interstate, interregional, and international in nature.

Water Resources

When unaffected by the activities of man, surface runoff is referred to as "natural" or "virgin" flow. Except in the headwater reaches, few streams in the Upper Colorado River Basin now carry their natural flow. Diversions, consumptive use, out-of-basin exports, and regulations by dams and reservoirs have reduced streamflows throughout the region. Consequently, the average annual virgin flow of the river can only be estimated by reconstruction from gaged flows and estimates of consumptive uses in the basin. The estimates (Upper Colorado River Commission 1973) of average annual virgin flow at Lee Ferry, Arizona, (Figure 4), show large variations from year to year. The average annual flows for various periods of record are shown in Figure 5. Extremes ranged from a high of 21.894 million acre-feet in 1917 to a low of 4.396 million acre-feet in 1934.

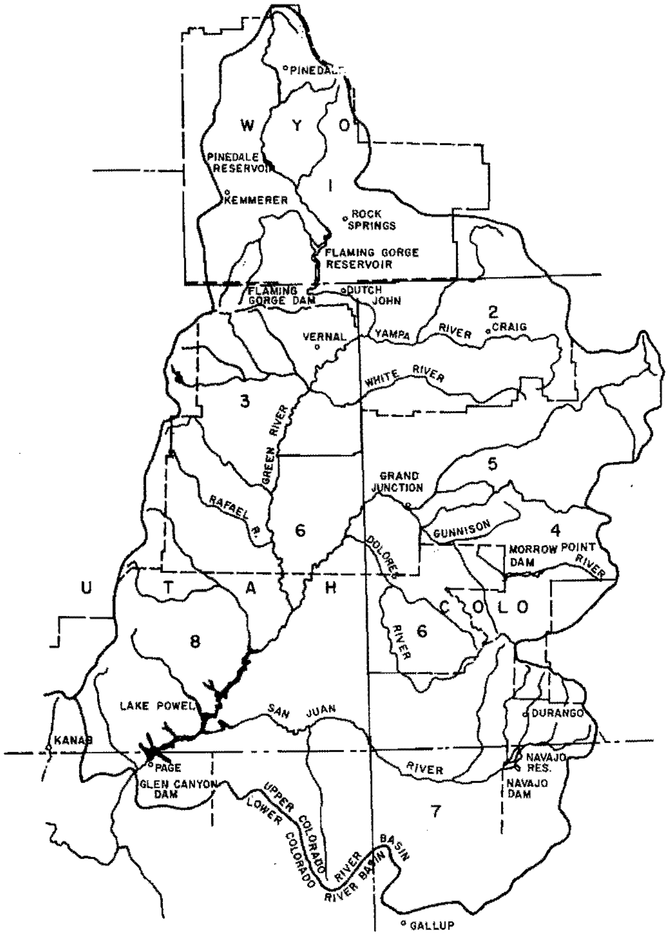

Figure 3. Water resources subareas for the Upper Colorado River Basin.

Analysis of the water allocation alternatives and their salinity impacts requires a combination of economic, water resources, and institutional data, all of which must be brought to a set of common geographical

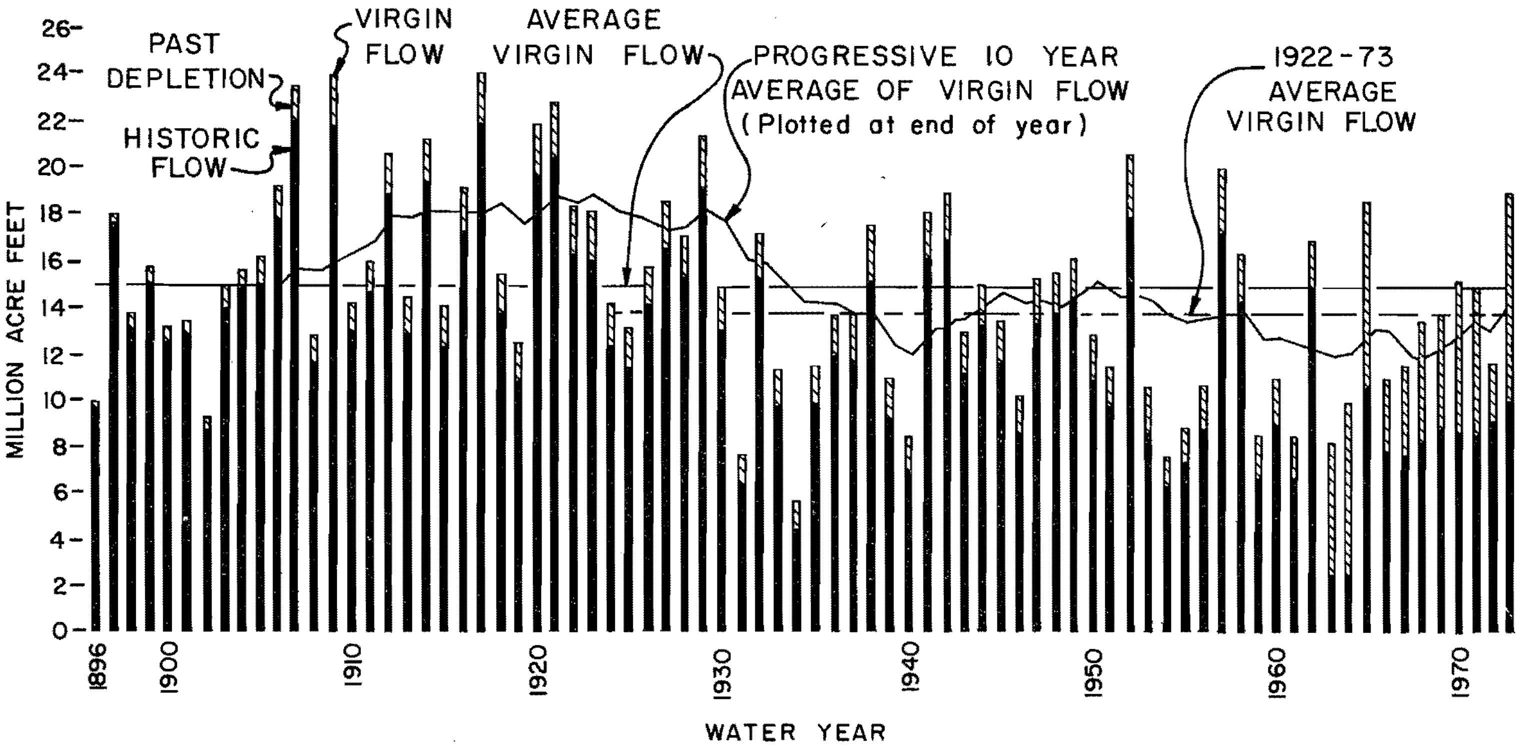

Figure 4. Colorado River flow at Lee Ferry, Arizona.

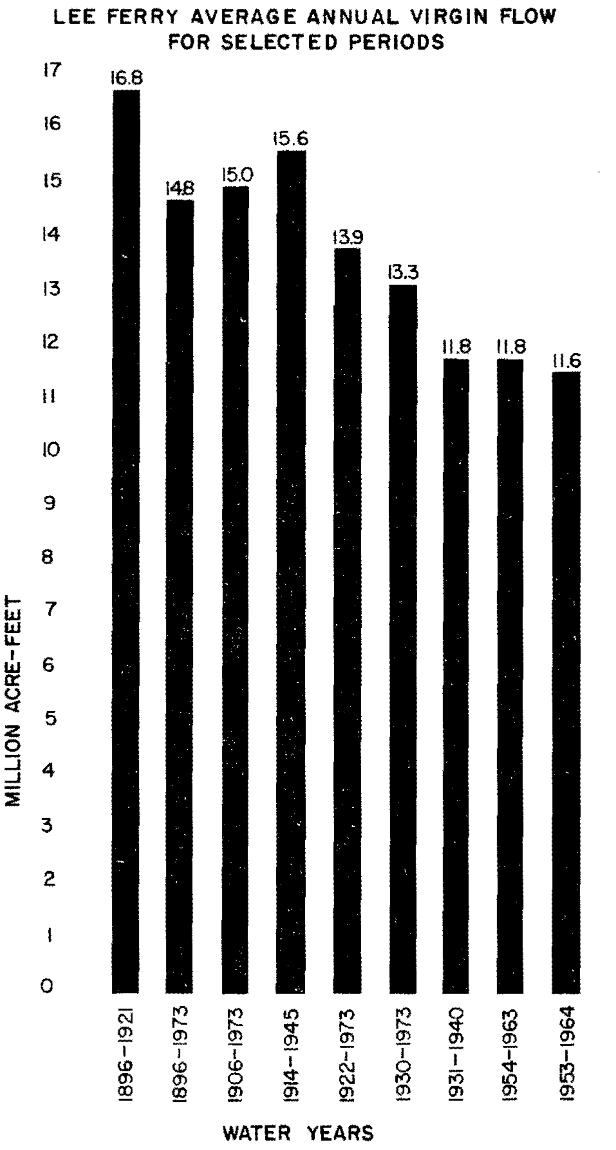

Figure 5. Lee Ferry average annual virgin flow for selected periods.

areas. Naturally, data available on stream flows and water quality are based on river basins. The Upper Colorado River Basin divides naturally into three major drainages, the Colorado River Main Stem (UM), the Green River (UG), and the San Juan River (US), and these are comprised of some 39 hydrologic subbasins. Water use and economic data, however, are more easily obtainable for political subdivisions. Most of these data are summarized by county or aggregated by larger regions along county boundaries (such as the Water Resources Subareas (WRSAs) and Aggregated Subareas (ASAs) used by the Water Resources Council 1972). Consequently, for purposes of organizing these data into common geographical subdivisions, WRSA 1401-1408 (1-8) are chosen as subareas in this study.

In order to estimate water availabilities for the analysis, the contribution to the natural river flow from each county was estimated. For this purpose the long term (1906-1973) average annual discharge of 14,994,200 acre-feet/year, used as the available supply in the Water Resources Council (1976) '75 Water Assessment Study, was taken as a base figure. Using hydrologic data on specific subregions (Table 1), irrigation consumptive use and exports were added to the gaged flow to estimate net basin contribution. This was proportioned upward to a total basin flow of 14.994 million acre-feet. Contributions of hydrologic subbasins were then aggregated to estimate the flow contributed by each WRSA. Similar calculations were made for 14.1 MAF and 13.8 MAF assumptions as shown in Table 2.

Superimposed on the natural hydrologic system are the water uses in the basin. A number of studies have attempted to estimate the withdrawals and consumptive uses of water for various purposes in the basin. A comprehensive set of estimates were made for the Upper Colorado River Framework Study based on 1965 data (U. S. Water Resources Council 1971). These data have been updated and modified by several recent studies (Colorado River Basin Salinity Control Forum 1975, Hyatt et al. 1970, U. S. Department of the Interior 1975, U. S. Water Resources Council 1976, 1977, Western States Water Council 1974).

Irrigation use

Irrigation is by far the largest consumptive use of water in the Upper Colorado River Basin, accounting for approximately 60 percent of the total depletion. Because of the arid nature of the entire region, the use of irrigation water on cropland is almost essential for significant production. Table 3 summarizes estimates of irrigation land and water use from the most recent studies. As shown in the table, the amount of irrigated land and water use in the Upper Basin has not increased appreciably over the last decade. In comparing the estimates, it should be noted that the data from the Agricultural Census are for water delivered to farms rather than consumptive use. These data are used to compute the irrigation consumptive use in Table 1 by disaggregating to county levels using Agricultural Census data. The water budgeting in Table 1 is used to derive the net availabilities in Table 2.

Other water uses

Water uses in the basin for purposes other than irrigation include municipal and industrial water supply, mining, livestock, recreation, fish and wildlife, and present energy development, mainly for coal-fired steam electric generation. The two largest sources of depletion other than irrigation

Table 1. Distribution of Colorado River flows.[a]

County/WRSA	Flow Contributed by County	Gaged[b] Flow	Δ[c] Flow	Irrigation Use[b]	Export[d]	Net Basin Contribution[e]	Adjusted Net Basin contribution[f]	Total Cumulative Flow	Hydrologic Subbasin
1 Sublette	1308.9	480	480	50		530	542.4	542.4	UG 1
		1115	634	110		744	761.6	1303.9	UG 2
2 Lincoln	30.7	1140	25	5		30	30.7	1334.6	UG 3
3 Sweetwater	164.8	28	28	30		58	59.4	59.4	UG 4
		1170	2	2		4	4.1	1398.1	UG 6
		1435	53	46		99	101.3	1814.6	UG 8
4 Uinta	315.2	212	212	96		308	315.2	315.2	UG 7
Subtotal 1401			1434	339		1773	1814.6		
5 Moffat	501.5	378	378	40		418	427.8	427.8	UG 9
		2910	62	10		72	73.7	3488.0	UG 11
6 Routt	1171.9	1035	1035	110		1145	1171.9	1171.9	UG 10
7 Rio Blanco	556.8	484	484	60		544	556.8	556.8	UG 15
Subtotal 1402			1959	220		2179	2230.1		
8 Uintah	110.6	41	41	47		88	90.1	90.1	UG 12
		3945	0	20		20	20.5	5089.8	UG 17
9 Duchesne	828.0	334	334	32	121	487	498.4	498.4	UG 13
		401	67	255		322	329.6	828.0	UG 14
10 Carbon	106.4	68	68	36		104	106.4	106.4	UG 16
11 Emery	175.0	105	105	66		171	175.0	175.0	UG 18
Subtotal 1403			615			1192	1220.0		
12 Gunnison Hinsdale	1006.0	604	604	67	1	672	698.4	698.4	UM 7
		855	251	45		296	307.6	1006.0	UM 8
13 Ouray	443.8	202	202	255		427	443.8	443.8	UM 9
14 Delta	808.6	1685	628	150		778	808.6	2258.4	UM 10
Subtotal						2173	2258.4		
15 Grand	523.8	160	160	28	316	504	523.8	523.8	UM 1
16 Summit	1339.6	1690	1190	130	50	1289	1339.6	2348.7	UM 3
17 Eagle	485.3	421	421	40	6	467	485.3	485.3	UM 2
18 Pitkin	1033.0	883	883	57	54	994	1033.0	1033.0	UM 4
19 Garfield	389.7	2860	287	88		375	389.7	3771.4	UM 5
20 Mesa	132.0	135	135	47		182	189.2	189.2	UM 6
		4440	-240	185		-55	-57.2	6161.9	UM 11
Subtotal 1405						3756	3903.5		
21 Delores San Miguel Montrose	662.0	605	605	32		637	662.0	662.0	UM 12
22 Grand	0	5040	-5	5		0	0	6823.9	UM 13
Subtotal 1406						637	662.0		
23 Archuleta	1386.9	505	505	18		523	662.4	662.4	US 1
		982	477	95		572	724.5	1386.9	US 2
24 San Juan (C) La Plata Montezuma	909.5	598	598	68		666	843.6	843.6	US 3
		19	19	30	3	52	65.9	65.9	US 5
25 San Juan (NM)	159.6	1601	21	27		48	60.8	2291.3	US 4
		1665	45	33		78	98.8	2456.0	US 6
Subtotal 1407						1939	2456.0		
26 San Juan (U)	506.6	1910	245	155		400	506.6	2962.6	US 7
27 Wayne Garfield Kane	-57.0	10880	-120	75		-45	-57.0	14994.2	UM 14
Subtotal 1408						355	449.6		
Basin Total						14004	14994.2		

Table 1. Continued.

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[a] Based on 1965 data

[b] Data from Hyatt et al. (1970)

[c] Net gaged flow from subbasin

[d] Data from U. S. Water Resources Council (1971)

[e] ΔFlow + Irrigation Use + Export

[f] Adjusted to WRC 1975 Assessment figures for ASA's [U. S. Water Resources Council (1976)]

Table 2. Flow contributions under different national flow assumptions (thousand acre-feet).

Counties/WRSA	14.9 MAF	14.1 MAF	13.8 MAF
1 Sublette	1303.9	1226.7	1200.6
2 Lincoln	30.7	28.2	27.6
3 Sweetwater	164.8	155.1	151.8
4 Uinta	315.2	296.1	289.8
Subtotal 1401	1814.6	1706.1	1669.8
5 Moffat	501.5	465.3	455.4
6 Routt	1171.9	1099.8	1076.4
7 Rio Bianco	556.8	521.7	510.6
Subtotal 1402	2230.2	2086.8	2042.4
8 Uintah	110.6	98.7	96.6
9 Duchesne	828	775.5	759
10 Carbon	106.4	98.7	96.6
11 Emery	175.0	169.2	165.6
Subtotal 1403	1220.0	1142.1	1117.8
12 Gunnison Hinsdale	1006.0	994.7	924.6
13 Ouray	443.8	423	414
14 Delta	808.6	761.4	745.2
Subtotal 1404	2258.4	2129.1	2083.8
15 Grand	523.8	493.5	483
16 Summit	1339.6	1254.9	1228.2
17 Eagle	485.3	451.3	441.6
18 Pitkin	1033.0	972.9	952.2
19 Garfield	389.7	366.6	358.8
20 Mesa	132.0	126.9	124.2
Subtotal 1405	3903.4	3666	3588
Delores 21 San Miguel Montrose	662.0	620.4	607.2
22 Grand	0	0	0
Subtotal 1406	662.0	620.4	607.2
23 Archuleta San Juan (C)	1386.9	1311.3	1283.4
24 La Plata Montezuma	909.5	860.1	841.8
25 San Juan (NM)	159.6	155.1	151.8
Subtotal 1407	2456	2326.5	2277
26 San Juan (U)	506.6	479.4	469.2
Wayne 27 Garfield Kane	-57.0	-56.4	-55.2
Subtotal 1408	449.6	423.0	414
Basin Total	14,994.2	14,100.0	13,800.0

Table 3. Summary of irrigation water use by aggregated subareas (ASA).

Item/ASA	'75 Assessment Study [22]	Hyatt, et al [10]	WRC Framework study [20]	Salinity forum [4]	1969 Ag Census Class 1-5 land [15]
Irrigated Area[a] (acres x 10^3)					
1401[b]	653	597.6	660.2		691.4
1402	490	570.4	583.9		472.4
1403	222	247.4	253.0		174.8
Total	1365	1415.4	1497.1		1338.6
Water Withdrawals (AF x 10^3)					
1401	4177.2	2352.8			
1402	2819.6	3378.2			
1403	1539.4	1012.2			
Total	8536.2	6743.2	5-7000		
Consumptive Use (AF x 10^3)					
1401	835.9	1015.0	818.4		1524.7
1402	940.2	1100.0	931.6		1354.5
1403	385.0	501.0	377.8		448.2
Total	2161.1	2616.0	2127.8[c]	2175.0	3327.4

Withdrawals (W) and Evapotranspiration (ET) in acre feet per acre

	W	ET	W	ET	W	ET	W	ET	W	ET
1401	6.4	1.3	3.9	1.7		1.2				
1402	5.8	1.9	5.6	1.9	N/A	1.6	N/A		N/A	
1403	6.9	1.7	4.8	2.0		1.5				
AVERAGE	6.3	1.6	4.8	1.9		1.4				

[a] In an average year there is estimated to be 124,400 acres of idle land which is not included

[b] ASA 1401, 1402, and 1403 are referred to the Green River, the Colorado River Main Stem, and the San Juan River Drainages respectively and the ASA numbers are different from WRSA numbers used in this study

[c] Includes incidental use and irrigation reservoir evaporation

are exports of water out of the basin to provide supplies to the large population centers on the east slopes of the Colorado Rockies and the Wasatch Front in Utah, and evaporation losses from main stem reservoirs of the Colorado Storage Project System.

Studies estimating the consumptive use for these various activities are in general agreement as to the magnitude of total depletions in the basin. The quantities are usually presented by state or by water resources ASAs and are, therefore, difficult to compare for smaller geographical areas. The levels of current depletions used in this study are those established by the 1975 Water Resources Assessment (U. S. Water Resources Council 1976, 1977).

Future expansion of nonenergy water use

Energy development constitutes a major demand for future water use, and the energy production activities will also expand needs for water in other sectors due to economic and population growth. In addition, there are a number of irrigation projects to which water has been committed (Hansen 1976, U. S. Department of the Interior 1977).

In order to provide for these future demands in the analysis, projected levels of water use for municipal, industrial, and other purposes compatible with the 1985 and 2000 energy scenarios are also estimated for the model. The projections for municipal and industrial water use are based on information from the 1975 Water Assessment. Future irrigation development is based on authorized projects as reported by the U. S. Department of the Interior and presented in Table 4. A summary of the information used for 1985 and 2000 levels of water use is presented in Table 5.

Upper Basin water supply - physical and legal considerations

The amount of water available to the Upper Basin states depends on both natural and legal considerations. Consequently, estimated amounts vary with the methods by which the studies were made and legal provisions interpreted. In addition to state laws which provide for intrastate control of water, use of water in the Upper Colorado River Basin is governed principally by three documents: the Colorado River Compact of 1922, the Mexican Treaty of 1944, and the Upper Colorado Basin Compact of 1948 (Hansen 1976). Among other provisions, the Colorado River Compact of 1922 apportions to the Upper and Lower Basins, each in perpetuity, exclusive beneficial consumptive use of 7,500,000 acre-feet of water annually from the Colorado River Basin. It further establishes the obligation of the Upper Basin states not to cause the flow of the Colorado River at Lee Ferry to be depleted below 75 million acre-feet for any period of 10 consecutive years. This provision is interpreted as requiring delivery of 7.5 MAF annually to the Lower Basin. The Mexican Treaty of 1944 guarantees Mexico delivery of 1,500,000 acre-feet of water annually from the Colorado River. The Upper Colorado River Basin Compact of 1948 divides the water apportioned to the Upper Basin among the Upper Basin states and establishes principles to govern deliveries of water to meet the Lee Ferry flow obligation. By the compact, the Upper Basin portion of Arizona is granted consumptive use of 50,000 acre-feet annually and the other states each receive percentages of the remaining consumptive use as follows: Colorado, 51.75 percent; New Mexico, 11.25 percent; Utah, 23.00 percent; and Wyoming 14.00 percent.

The two most familiar and widely accepted figures for the annual Upper Colorado River Basin water supply are the Department of Interior's 5.8 MAF and the Upper Colorado River Commission's 6.3 MAF (Hansen 1976). The Department of the Interior figure is based on delivery of 8.25 MAF to the Lower Basin. Of this, 0.75 MAF is to satisfy the Mexican Treaty and operate storage projects to meet Upper Basin needs and downstream obligations through critical low-flow periods. The 6.3 MAF suggested by the study for the Upper Colorado River Commission is based on delivery of 7.5 MAF per year to the Lower Basin with no allowances made to satisfy the Mexican Treaty and with no shortages required of Upper Basin users. If these differences in operating assumptions are

Table 4. Project of new irrigation lands (acres).

Subbasin and County	1985	2000
Subbasin 1	0	0
Subbasin 2		
Savery - Pot Hook (Moffat)	14,400	0
Subbasin 3		
Uintah Unit (Duchesne)	7,800	0
Deferred Indian lands	17,000	4,300
Central Utah Project - Jensen Unit (Uintah)	440	0
Subbasin 4		
Fruitland Mesa (Gunnison)	11,300	600
Subbasin 5		
West-Divide (Garfield - C)	9,000	3,700
Subbasin 6		
Monderu (Delores)	34,000	1,360
San Miguel (San Miguel)	11,500	0
Subbasin 7		
Navajo Indian Irrigation (San Juan - NM)	72,000	0
Animas - La Plata (La Plata)	46,000	0
Total	223,440	9,960

Source: U.S. Department of the Interior, Quality of Water Colorado River Basin, Progress Report No. 8, January 1977, p. 63.

Table 5. Summary of future water development over 1975 base year.

County	Additional Depletion - 1985 (10^3 AF/year)						Additional Depletion - 2000 (10^3 AF/year)					
	M&I	Export	Fish & Wildlife	Mining	Total	Irrigation	M&I	Export	Fish & Wildlife	Mining	Total	Irrigation
1 Sublett					0							
2 Lincoln	2.0		20	79	101.0		1.2		20	254.8	276.0	
3 Sweetwater	2.3				2.3		4.3				4.3	
4 Uinta					0	4	.6				.6	4
Subtotal 1401						4						4
5 Moffat	.2	9			9.2	20	.3	24			24.3	22
6 Routt	.1				.1		.3				.3	
7 Rio Blanco	.3				.3		.7				.7	
Subtotal 1402						20						22
8 Uintah	.5				.5	15[b]	5.8				5.8	15
9 Duchesne	.5	146[a]			146.5	80[c]	1.0	146			147.0	90
10 Carbon	.5				.5		1.5				1.5	
11 Emery	1.5				1.5		2.0				2.0	
Subtotal 1403						95						105
12 Gunnison Hinsdale	.4				.4	33	1.7				1.7	38
13 Ouray							.5				.5	
14 Delta	.4				.4		.6				.6	
Subtotal 1404						33						38
15 Grand	45				45.0		45				45.0	
16 Summit		158			158.0			218			218.0	
17 Eagle											0	
18 Pitkin		40			40.0			40			40.0	
19 Garfield	4.6				4.6	33	7.0				7.0	50
20 Mesa	.4				.4		.6				.6	
Subtotal 1405						33						50
21 Delores San Miguel Montrose		102			102.0	53		105			105.0	67
22 Grand					0						0	
Subtotal 1406						53						67
23 Archuleta					0						0	
24 San Juan (C) La Plata					0	146	.9				.9	153
25 Montezuma San Juan (NM)	8	20			28.0	231	8	20			28.0	231
Subtotal 1407						377						384
26 San Juan (U)					0						0	
27 Wayne Garfield Kane	2.6				2.6		5.5				5.5	
Subtotal 1408												
Basin Total						615						670

[a] Bonneville Export

[b] Jensen Unit

[c] Upalo, Unita, Deferred Indian Water Rights

[1] '75 Water Assessment - Tech Memo 3, U. S. Department of the Interior (1977)

taken into account, the results of these two studies yield essentially the same estimates of average annual flows.

Cases for model analysis

The most accepted interpretations of the legal and institutional constraints and assumptions of available water supply were used to construct five cases for analysis (Table 6). From the net state shares in Table 6, municipal, industrial, and other consumptive uses are subtracted to estimate the net water available for energy or agriculture in Table 7. In each case, the total water depletions must be less than a state's compact entitlement.

Case 1. This case takes the most optimistic view of the available water supply using the long term average of 14.994 MAF. From this is deducted the Lower Basin share of 7.5 MAF, half of the Mexican Treaty obligation of 0.75 MAF, and 0.05 MAF for Arizona's entitlement (a total of 8.3 MAF) to leave 6.694 MAF to apportion by the percentages for the Upper Basin states. The final figure for water availability for energy and agriculture for 1975, 1985, and 2000 is obtained by subtracting all other projected uses from the state apportionment.

Table 6. Water shares of Upper Basin States under different supply and institutional assumptions (AF x 10^3).

		States			
	Basin Total	Colorado (51.75%)	New Mexico (11.25%)	Utah (23.00%)	Wyoming (14.00%)
CASE 1					
Average Annual Flow	14,994				
Lower Basin Share	8,300[a]				
Upper Basin Shares	6,694	3464	753	1540	937
Main Stem Evaporation	520	269	58	120	73
Net State Shares	6,174	3195	695	1420	364
CASE 2					
Average Annual Flow	14,000				
Lower Basin Share	7,550				
Upper Basin Shares	6,450[b]	3338	726	1483	903
Main Stem Evaporation	520	269	58	120	73
Net State Shares	5,930	3069	668	1363	830
CASE 3					
Average Annual Flow	14,050				
Lower Basin Share	8,300				
Upper Basin Shares	5,750[c]	2976	647	1322	805
Main Stem Evaporation	520	269	58	120	73
Net State Shares	5,230	2707	589	1202	732
CASE 4					
Average Annual Flow	13,800[d]				
Lower Basin Share	8,300				
Upper Basin Shares	5,500	2846	619	1265	770
Main Stem Evaporation	520	269	58	120	73
Net State Shares	4,980	2577	561	1145	697
CASE 5					
Average Annual Flow	13,800				
Lower Basin Share	7,550				
Upper Basin Shares	6,250	3234	703	1437	875
Main Stem Evaporation	520	269	58	120	73
Net State Shares	5,730	2965	645	1317	802

[a] Lower Basin = 7.5 MAF, Mexico = 0.75 MAF, and Arizona = 0.05 MAF

[b] Upper Colorado River Commission estimate of 6.5 MAF less 0.05 MAF to Arizona

[c] Bureau of Reclamation conservative hypothesis of 5.8 MAF less 0.05 MAF to Arizona

[d] Average virgin flow since Colorado River Compact (1922-1975)

Table 7. Net water available for energy and irrigation under different supply and institutional assumptions (AF x 103).

		1975		1985		2000	
State	Net State Share[a]	Consumptive Use[b]	Net Available[c]	Consumptive Use[b]	Net Available[c]	Consumptive Use[b]	Net Available[c]
Case 1							
Colorado	3195	604	2591	964	2231	1048	2147
New Mexico	695	97	598	125	570	125	570
Utah	1420	156	1264	308	1112	320	1100
Wyoming	864	41	823	144	720	322	542
CASE 2							
Colorado	3069	Same	2465	Same	2105	Same	2021
New Mexico	668		571		548		543
Utah	1363		1207		1055		1043
Wyoming	830		789		686		508
CASE 3							
Colorado	2702	Same	2100	Same	1743	Same	1659
New Mexico	589		492		464		464
Utah	1202		1046		894		882
Wyoming	732		649		588		410
CASE 4							
Colorado	2577	Same	1973	Same	1613	Same	1529
New Mexico	561		464		436		436
Utah	1145		989		837		825
Wyoming	697		656		553		375
CASE 5							
Colorado	2965	Same	2361	Same	2001	Same	1917
New Mexico	645		548		520		520
Utah	1317		1161		1009		997
Wyoming	802		761		658		480

[a] From Table 6
[b] Sums nonirrigation and non-energy consumptive use, i.e., municipal, industrial, export, etc.
[c] Net water available for energy or irrigation use under the case assumptions

Case 2. This case uses the Upper Colorado River Commission's estimate of 6.5 MAF for the available supply. This is based on 7.5 MAF to the Lower Basin, but no provision for the Mexican Treaty.

Case 3. This case is based on the Bureau of Reclamation's conservative hypothesis of 5.8 MAF for the Upper Basin supply. Since it implicitly assumes 8.3 MAF for downstream commitments, the total basin supply is taken to be about 14.1 MAF. After the 5.8 MAF is apportioned among the Upper Basin states, nonenergy and nonagricultural uses are deducted.

Case 4. This case uses the average virgin flow since the enactment of the Colorado River Compact (1922-1975) of 13.8 MAF, and downstream commitments of 8.3 MAF. The remaining 5.5 MAF makes this the most stringent case so far as water availability for the Upper Basin.

Case 5. The final case uses the same virgin flow as Case 4, but downstream commitments are taken to be 7.5 MAF for the Lower Basin and 0.05 MAF for Arizona. No provision is made for the Mexican Treaty.

Only three cases seem to involve critical water supply conditions (cases 1, 3, and 4) and therefore they were selected for use in the model analysis.

Water Quality and Legal Aspects

Some surface and subsurface flow into the Colorado River contain large amounts of dissolved salts. The salt concentration generally increases from the headwater areas to downstream. The rate of increase is directly related to the geologic character of the terrain across which the Colorado River and its tributaries flow. In the lower portions of the Upper Basin, there are several areas of shallow shale deposits where the salts are readily dissolved by water movement across or through the soil profile. In addition to the natural loadings, human activities increase salinity levels through both salt loading and salt concentrating processes.

The salinity of streams in the Upper Basin varies from day to day and month to month with fluctuations in the streamflow and salt loadings. Total annual salt load, outflow, and average salinity concentration level of each WRSA (Utah State University 1975) are presented in Figure 6.

Since the increases in salinity levels cause economic damages to the Lower Colorado River Basin and Mexico, a need for mitigation has lead to the salinity-control efforts described in three important documents:

1) The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) and the Clean Water Act of 1977 (Public Law 95-217) seek to restore and maintain the chemical, physical, and biological integrity of the nation's waters. Public Law 92-500 declares that the national goal is to eliminate discharge of pollutants into navigable waters by 1985. This legislation has been interpreted by the Environmental Protection Agency (EPA) to require that numerical standards for maximum allowable salinity concentrations on the Colorado River be set. An agreement reached between EPA and the Upper Basin states in 1974 calls for the maintenance of salinity at or below 1972 levels. Later, in 1976, EPA issued standards for three locations (723 mg/l below Hoover Dam, 747 mg/l below Parker Dam, and 879 mg/l at Imperial Dam).

2) Minute No. 242, an agreement made in 1973, promises that the salinity of water delivered to Mexico will not exceed 115 parts per million (ppm) ± 30 ppm over the annual average salinity of Colorado River water which arrives at Imperial Dam.

3) The Colorado River Basin Salinity Control Act (Public Law 93-320) authorizes the Secretary of the Interior to construct several projects for the improvement, enhancement, and protection of the quality of water available in the Colorado River for use in the United States and the Republic of Mexico.

Under Public Law 93-320, the Colorado River Salinity Control Program has been established, and several projects are authorized for planning or construction to reduce salt loading from natural sources. Whether these public investments prove economically feasible will depend on their cost and the benefits received. A list of the proposed projects with associated costs, water losses, and salt reductions is shown in Table 8.

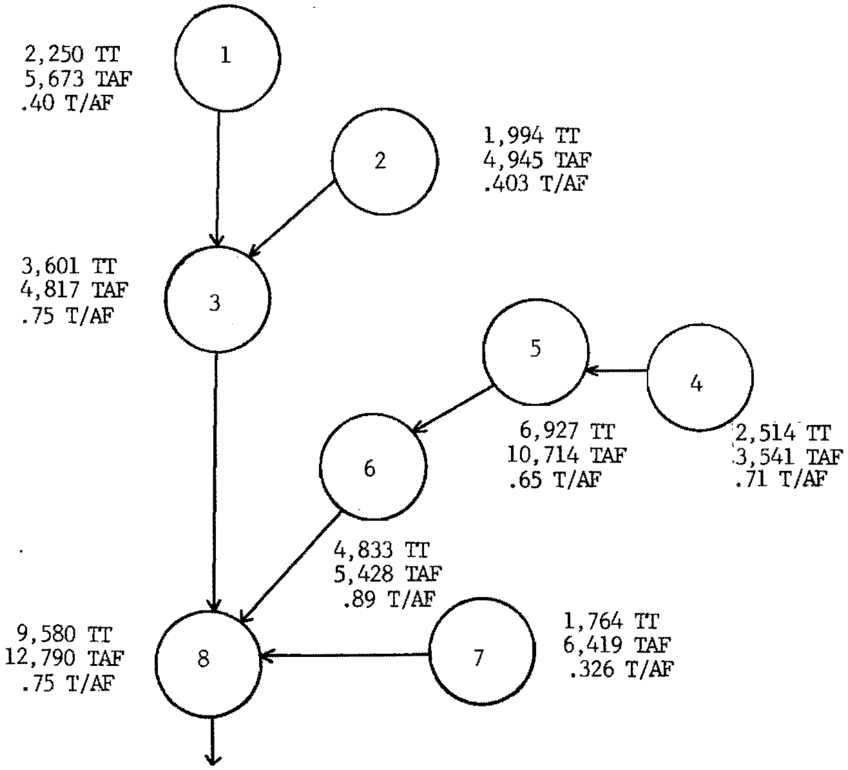

Figure 6. Thousand tons (TT) of salt load, thousand acre-feet (TAF) of outflow, and ton per acre foot (T/AF) of salinity level of each WRSA.

Table 8. USDI-Bureau of Reclamation's projects authorized and planned for construction estimated potential effects and costs of construction.

WRSA	Units	Type of Project	Estimated Salt Reduction (1,000 tons/yr)	Construction Cost ($1,000,000)	Annual OM & R Cost ($1,000,000)	Total Annual Equivalent Cost[1] ($1,000,000)	Cost Dollars/Ton	Water Loss (AF)
1	Big Sandy River	Desalting	80	Not available				6,000
3	Uintah Basin	IMS & WSI[2]	100	Not available				
	Price & San Rafael River	Under investigation	180	Not available				5,000 to 30,000 ea.
5	Grand Valley	IMS & WSI	200	81.3	0.0[3]	4.58	23	
	Glenwood-Dotsero Springs	Desalting	250	69.5		16.30	65.2	
6	Paradox Valley	Evaporation pond	180	21.1	.541	1.638	9.1	4,000
	Crystal Geyser	Evaporation pond	3	2.69	.016	.167	56.0	150
	Lower Gunnison Basin	IMS & WSI	300	Not available				
7	McElmo Creek	Ponding & Desalting	40				30.0	6,200
8	Dirty Devil River	Under investigation	80	Not available				

1. Includes interest during construction at 5.625%.
2. Irrigation management services and water system improvements.
3. The O & M cost of IMS (estimated $240,000) will be offset by a reduction in distribution system O & M.

Sources: Department of the Interior, Status Report and Quality of Water Colorado River Basin, Progress Report No. 8.

Economic Activities of the Basin

Agriculture

Agriculture in the Upper Colorado River Basin consumes a major portion of the water depletions. Further, salt loading from return flows is estimated to be 30 percent, which significantly affects the water quality of the river. This sector is the most promising potential supplier of water for energy development in the basin as well as a promising candidate for salinity control measures to upgrade river water quality.

Irrigation has played an important role in the development of the Upper Basin. Because of its arid climate, irrigation is essential for crop production. The principal sources of water are the streams fed by melting mountain snows. Irrigated lands are generally located along streams where water can be diverted conveniently. Most crop fields are supplied by dirt ditches and flood or furrow irrigated. Less than 10 percent of the crop acreage is sprinkler irrigated. This results in low efficiency of water use. Lengths of unlined canals and irrigation efficiencies by county are presented in Table 9. Only 14 percent of total length of canal (13,839 miles) is lined, and the overall average irrigation efficiency is 0.46. This efficiency, however, represents the fraction of the water diverted that is consumed in crop production by the diverting irrigator. Irrigation efficiency on a basinwide basis is much higher because the return flows from upstream irrigators provide the water supply for those downstream.

An estimated 2.7 MAF of water was applied to crop land in 1974. Some of this was returned to the stream, and most of the rest was used by plants in the evapotranspiration process. Evapotranspiration or consumptive use is defined as the water used by growing vegetation due to transpiration through plant foliage and evaporation from the plant and surrounding environment (Hyatt et al. 1970). The rate of consumptive use depends on the type and density of crop, soil moisture supply, soil salinity, and climate. In addition, consumptive use losses occur as water is taken by weeds or other nonproductive plants. Climatological parameters influencing water consumption are precipitation, temperature, daylight hours, solar radiation, humidity, wind velocity, cloud cover, and length of growing season. The yearly average water consumptive uses (acre-feet) for various crops have been estimated (Table 10). The amounts vary with the climatic differences among the subbasins.

Crops grown are primarily forage and feed for livestock, the major agricultural activity in the Upper Colorado River Basin. Alfalfa hay and and native hay are the main hay crops grown; in 1974 they used about 58 percent of the irrigated land. Pasture and small grains ranked second and third among the irrigated crops produced in the basin. Barley and wheat were the primary grains for feed. Total acreages of irrigated land used to grow selected field crops in 1974 are shown in Table 11. Since several field crops are included due to insignificant amounts of land use and lack of production cost data, total acreages of irrigated land in this study may be less than in other documents.

The irrigation water not consumed by the crops nor wasted as evapotranspiration by nonproductive plants ends up as either surface runoff or percolation through the soil, beyond the root zone. The unconsumed water usually finds its way back to streams. Loss of water to evapotranspiration increases salinity levels downstream via the salt concentrating effect. Movement of water through the soil also collects salts and carries them back to the stream through return flows. Hence, irrigation generally increases salinity downstream by both salt loading and salt concentrating mechanisms. The salinity increase caused by irrigated agriculture has been estimated to be between 17 to 37 percent in the Upper Colorado River Basin. Energy development decisions need to consider effects on salinity as well as those on water supply.

Energy

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 extensive and commercially important mineral resources of the Upper Basin are coal, oil, and natural gas. The recent nationwide shortage of energy has resulted in an intensive search for expansion of old sources and location of new sources. As a result, investigations are underway for the commercial development of shale oil in Colorado, Utah, and Wyoming. Several coal-fired electric generating plants are either being constructed or are in the planning stages for construction. Coal gasification is another energy industry being planned for Wyoming and New Mexico.

Decisions on whether or not to develop these resources depend largely upon economic feasibility and environmental impacts. Water resource and water quality are important to both determinations. Water is an important input in energy production. Each process requires water, and total water requirements per unit of output have been estimated (Table 12).

Water pollution problems, arising from the production of various energy related products, are of major concern. Sources of pollution include surface disturbances producing sediments and salt, mine drainage producing heavy metals and other toxics, and wastewater discharges containing organic and carcenogenic agents and causing increases in

Table 9. Unlined canal and irrigation efficiency in the Upper Colorado River Basin.

WRSA		County	Unlined Canal (miles) Length	Total	Irrigation Efficiency River Basin	Average	River Basin	Sub-basin No.
1	1	Sublette	126.10	734	0.22	.4	New Fork	UG 1
			271.6		0.34		Green River above LaBarge	UG 2
	2	Lincoln	9.7		0.47		Green River above Fontenelle	UG 3
	3	Sweetwater	58.2		0.46		Big Sandy Creek Basin	UG 4
					0.22		Green River above Green River	UG 6
			72.75		0.51		Green River above Flaming Gorge	UG 8
	4	Uinta	194.0		0.68		Black Fork	UG 7
2	5	Moffat	63.05	708	0.36	.37	Little Snake	UG 9
			45		0.42		Green River above Jensen	UG 11
	6	Routt	416.5		0.39		Yampa	UG 10
	7	Rio Blanco	183.3		0.35		White	UG 15
3	8	Uintah	205	2,000	0.61	.55	Ashley Creek Basin	UG 12
			150		0.53		Green River above Green River	UG 17
	9	Duchesne	135		0.39		Duchesne River above Duchesne	UG 13
			1,065		0.49		Duchesne River above Randlett	UG 14
	10	Carbon	145		0.63		Price	UG 16
	11	Emery	300		0.50		San Rafael	UG 18
4	12	Gunnison	364.5	1,741	0.20	.42	Tomichi Creek Basin	UM 7
		Hinsdale	418.6		0.42		Gunnison River above North Fork	UM 8
	13	Ouray	696.4		0.25		Uncomphagre	UM 9
	14	Delta	261.0		0.34		Gunnison River above Grand Junction	UM 10
5	15	Grand	182.3	3,572	0.32	.36	Colorado River above Hot Sulphur Springs	UM 1
	16	Summit	565.7		0.36		Colorado River above Glenwood Springs	UM 3
	17	Eagle	168.3		0.27		Eagle	UM 2
	18	Pitkin	224.4		0.42		Roaring Fork	UM 4
	19	Garfield	420.8		0.60		Colorado River above Plateau Creek	UM 5
	20	Mesa	168.3		0.72		Plateau Creek Basin	UM 6
			1,841.4		0.31		Colorado River above Colorado-Utah Line	UM 11
6	21	Delores San Miguel Montrose	115	171	0.6	.60	Dolores	UM 12
	22	Grand	55.8		0.54		Colorado above Cisco	UM 13
7	23	Archuleta	110.4	1,541	0.3	.43	San Juan above Arboles	US 1
			590.4		0.43		San Juan above Archuleta	US 2
		San Juan (C)	307.2		0.42		Animas	US 3
	24	La Plata	283.2		0.55		La Plata	US 5
		Montezuma	115.2		0.55		San Juan River above Farmington	US 4
	25	San Juan (NM)	134.4		0.51		San Juan River above Shiprock	US 6
8	26	San Juan (U)	450.8	1,384	0.57	.53	San Juan River above Bluff	US 7
	27	Wayne Garfield Kane	933.1		0.51		Colorado River above Lees Ferry	UM 14

Source: Utah State University, Colorado River Regional Assessment Study, Part One, 1975. pp. 129-131.

temperature. Moreover, the energy industries' large diversion and consumptive use of water decreases the stream's capacity for assimilating those discharges.

Beneficial uses of water in the Upper Colorado River Basin for agricultural and energy development activities inevitably increase salinity levels downstream if no control measures are undertaken. A mathematical model will be formulated to determine the impact of water uses on salinity levels and to derive least-cost salinity control measures to reduce those impacts.

Table 10. Consumptive use (acre-feet per acre per year) during an average growing season in the eight subbasins.

	Alfalfa						Corn			
Subbasin	Full	Partial	Barley	Wheat	Oat	Nursecrop	Grain	Silage	Potato	Pasture
1	2.10	1.10	1.20	1.67	1.60	1.60	-	-	1.75	1.75
2	1.95	0.90	1.20	1.67	1.60	1.60	-	-	1.75	1.70
3	2.10	1.10	1.20	1.67	1.60	1.60	2.08	1.4	1.75	1.80
4	2.00	1.00	1.20	1.67	1.60	1.60	2.08	1.3	1.83	1.70
5	2.00	1.00	1.20	1.67	1.60	1.60	2.08	1.3	1.83	1.70
6	2.80	1.90	1.40	1.67	1.60	2.00	2.08	1.8	1.83	2.20
7	1.90	0.90	1.30	1.67	1.60	1.60	2.08	1.8	1.83	2.00
8	1.90	0.90	1.30	1.67	1.60	1.60	-	2.08	1.83	2.00

Source: U.S. Water Resources Council, Upper Colorado Region Comprehensive Framework Study, 1971, and Paul Christensen, Seasonal Consumptive Use of Water for Crops in Utah in Inches During the Frost-free or Growing Period, 1977.

Table 11. Total acreages of irrigated land used for selected field crops.

WRSA	Alfalfa Hay	All Hay (Except Alfalfa)	Pasture	Small Grains*	Corn Grain	Corn Silage	Potatoes	Total
1	51,456	188,147	89,084	11,327	109	58	4	340,185
2	20,947	50,876	19,640	1,677	195	365	14	93,714
3	52,747	23,014	72,033	9,049	2,205	7,671	11	166,730
4	19,743	46,580	36,389	6,499	3,347	4,156	53	116,767
5	65,033	51,356	51,569	6,730	8,155	6,219	108	189,170
6	21,632	9,864	28,189	22,675	3,877	7,713	2,613	96,563
7	30,123	14,608	52,025	5,355	747	2,956	178	105,992
8	15,170	2,545	12,110	4,068	0	915	112	34,920
Total	276,851	386,990	361,039	67,380	18,635	30,053	3,093	1,144,041

Source: U. S. Department of Commerce, Bureau of Census, 1974 Census of Agriculture.

*Small grains include barley, wheat, oats, rye, and sorgham for all purposes.

Table 12. Water requirement for energy production.

Activity	Water Requirement	Plant Size
Extraction		
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	61.38 AF/10^6 bbls	
Oil shale	15,000 AF/yr	100,000 bbl/day
Conversion		
Coal-fired electric generating	12.2 AF/yr MWe	
Coal gasification	9,000 AF/yr	250 MMcfd
Oil refinery	43 gallons/bbl	
Nuclear	22,000 AF/10^3 MWe	

Source: Bruce Bishop and Rangesan Narayanan, "Energy Development Impacts on Agricultural Water Use" in Journal of Irrigation and Drainage Division, ASCE, (forthcoming).

IV. MODEL FORMULATION FOR THE STUDY AREA

A linear programming (LP) approach is employed to model the allocation of water between agricultural and energy production. Within the LP framework, the optimal allocation of water use among water users in the Upper Basin, from the private viewpoint, is calculated by maximizing joint net returns for agricultural and energy products within appropriate constraints. The resulting change in salinity level downstream is then estimated through a mass-balance approach. The model will be later modified to incorporate salinity control measures to evaluate least-cost strategies and to identify optimal salinity levels.

For the purpose of this analysis, the following constraints are used:

1. Complete voluntary transfer of water rights is allowed within each state, but interstate transfers are not permitted due to institutional constraints.

2. In compliance with Public Law 92-500, aimed at elimination of waste discharges by 1985, wastewaters from energy development will not be discharged into rivers. Energy developers are assumed to provide total containment of the wastewater.

3. Water available for agriculture and energy sectors is the water remaining after withdrawal for municipal and industrial needs, for exports, and for wildlife conservation.

4. Both agriculture and energy sectors are price takers in input and output markets.

The Objective Function

Maximizing joint net returns of agricultural and energy outputs can be accomplished by the following approach:

Net return of agricultural outputs

The economic returns accruing to agricultural crops are determined by the yield or land productivity for the crops. The Upper Colorado River Basin is subdivided into eight Water Resources Subareas (WRSA) (s = 1, 2, . . ., 8) along county boundaries (Figure 3). Suppose each WRSA grows H different crops (i = 1, 2, . . ., H). If P_i^s is the unit price of the ith crop and X_i^s is the acreage of land used in growing the ith crop with δ_i^s productivity (units of the ith crop per acre) in the sth WRSA, the gross return to agriculture for the entire basin is

$$TR_A = \sum_{s=1}^{8} \sum_{i=1}^{H} P_i^s \delta_i^s X_i^s \tag{1}$$

The cost associated with growing crop i comes from using various inputs such as seed, fertilizer, labor, land, and machinery. If C_i^s is the unit cost of growing the ith crop per acre, the total cost of production can be expressed as

$$TC_A = \sum_{s=1}^{8} \sum_{i=1}^{H} C_i^s X_i^s \tag{2}$$

The difference between total gross return and total cost yields the net return of agricultural output π_A

$$\pi_A = TR_A - TC_A \tag{3}$$

Net return of energy outputs

Suppose there are M raw energy outputs (r = 1, 2, . . ., M) that can be sold directly in the market after extraction from the ground and there are N final outputs (k = 1, 2, . . ., N) from energy conversion processes. Let P_r^s and R_r^s be the price and quantity, respectively, of the rth raw energy outputs, and P_k^s, Q_k^s be the price and quantity of the kth converted product in WRSAs. The total revenue from energy products is written as

$$TR_E = \sum_{s=1}^{8} \sum_{r=1}^{M} P_r^s R_r^s + \sum_{s=1}^{8} \sum_{k=1}^{N} P_k^s Q_k^s \tag{4}$$

If C_r^s and C_k^s are the unit costs of all factors, other than raw material, used in the extraction and conversion process in the sth WRSA, the total cost of producing energy output is

$$TC_E = \sum_{s=1}^{8} \sum_{r=1}^{M} C_r^s R_r^s + \sum_{s=1}^{8} \sum_{k=1}^{N} C_k^s Q_k^s \qquad (5)$$

However, for energy conversion, a firm can purchase raw energy material either within the WRSA (s) or from another WRSA (u). The purchasing decision will depend upon the cost of extraction and transportation of that raw material. Let T_t be the unit cost of transportation mode t. Transportation cost within the WRSA is included in the cost of conversion. The TC_E can be rewritten as

$$TC_E = \sum_{s=1}^{8} \sum_{r=1}^{M} C_r^s R_r^s + \sum_{s=1}^{8} \sum_{k=1}^{N} C_k^s Q_k^s + \sum_{s=1}^{8} \sum_{\substack{u=1 \\ s \neq u}}^{8} (C_r^s + T_{t,r,k}^{s,u}) R_{r,k}^{s,u} \text{ for all } t \qquad (6)$$

The net return of energy output (π_E) is the difference between total revenue and total cost:

$$\pi_E = TR_E - TC_E \qquad (7)$$

Adding Equations 3 and 7 yields the joint net return of agricultural and energy products which will be maximized. The objective function Z is written as:

$$\text{Max } Z = \pi_A + \pi_E$$

Substituting Equations 1, 2, 4, and 6 into the objective function and rearranging the terms, the objective function can be written as:

$$\text{Max } Z = \sum_{s=1}^{8} \sum_{i=1}^{H} (P_i^s \delta_i^s - C_i^s) X_i^s + \sum_{s=1}^{8} \sum_{r=1}^{M} (P_r^s - C_r^s) R_r^s + \sum_{s=1}^{8} \sum_{k=1}^{N} (P_k^s - C_k^s) Q_k^s - \sum_{s=1}^{8} \sum_{\substack{u=1 \\ s \neq u}}^{8} (C_r^s + T_{t,r,k}^{s,u}) R_{r,k}^{s,u}$$

Basic Constraints

Agricultural production

Land. Irrigated land is classified between cropland (L_c) and pasture land (L_p). Acreage of land irrigated for fieldcrops and pasture production cannot exceed the total irrigated acreage in each WRSA.

$$\sum_{i=1}^{H-1} X_i^s \leq L_c^s$$

$$X_P^s \leq L_P^s \qquad (8)$$

Crop rotations. The proper crop rotation is required for diversification purposes and to maintain the quality of soil. From the report of the U. S. Department of Agriculture, Soil Conservation Service (1974) and the observed production in 1974, the specific rotational constraints are written in terms of acreage as:

$$5 \text{ Nurse crop} - \text{Alfalfa} \geq 0$$

$$5 \text{ Oat} + 5 \text{ Barley} - 2 \text{ Alfalfa} \leq 0$$

$$\text{Alfalfa} + \text{Wheat} + \text{Barley} + \text{Oat} - 8 \text{ Corn grain} - 8 \text{ Corn silage} \geq 0 \qquad (9)$$

Energy production

Energy output flow.

$$R_r^s + \sum_{u=1}^{8} \sum_{k=1}^{N} R_{r,k}^{s,u} - I_r^s = 0 \qquad s=1, \ldots, 8 \quad r=1, \ldots, M \qquad (10)$$

The quantity of the rth raw material directly sold in the market plus the sum of the raw material flows to all conversion processes in the basin must equal total output (I) of the rth extraction process.

Conversion process efficiency.

$$\eta_k^s \sum_{u=1}^{8} \sum_{r=1}^{M} R_{r,k}^{s,u} - Q_k^s = 0 \qquad k=1, 2, \ldots, N \quad s=1, 2, \ldots, 8 \qquad (11)$$

The efficiency (η) of the kth energy conversion process multiplied by the sum of purchased raw energy material from all WRSAs used in this process equals the final output of that process.

Capacity. The quantity of raw material extracted from the ground must be less than or equal to the resource availability (D_r)

$$I_r^s \leq D_r^s \qquad r=1, 2, \ldots, M \qquad (12)$$

The final energy output from the kth conversion process is subject to the capacity of that processing plant (B_k)

$$Q_k^s \leq B_k^s \qquad k=1, 2, \ldots, N \qquad (13)$$

Water requirements and availabilities

Water requirement for agriculture. Let ϕ_i be the water consumptive use per acre required by crop i. The total water consumptive use by agricultural production, W_A,. in WRSAs is:

$$\sum_{i=1}^{H} \phi_i^s X_i^s = W_A^s \qquad s=1, 2, \ldots, 8 \tag{14}$$

Crops consume only a fraction of the water diverted (W_D). The water consumed by crops and other incidental consumptive uses divided by water diversions gives the overall irrigation efficiency (α). Water which is not consumed by crops returns to the natural stream and becomes a source of water supply to downstream users.

$$(1 - \alpha^s)W_D^s - W_{RF}^s = 0$$

and, therefore

$$\alpha^s W_D^s - W_A^s = 0 \tag{15}$$

where W_{RF}^s is the return flow of the s^{th} WRSA.

Water requirement for energy. If g_r and h_k are the amounts of water required to produce one unit of raw material and one unit of final output, respectively, the total quantity of water required in the energy production of each WRSA is

$$\sum_{r=1}^{M} g_r^s I_r^s + \sum_{k=1}^{N} h_k^s Q_k^s = W_E^s \qquad s=1, 2, \ldots, 8 \tag{16}$$

Water availabilities. Using the flow balance approach, the total water consumptive use in agricultural and energy productions plus the natural outflow ($F^{s,s+1}$) from upper WRSA and return flow to lower WRSA yields the total surface water availability (W_o) of the s^{th} WRSA:

$$W_A^s + W_E^s + F^{s,s+1} - \sum_{\substack{u=1\\u>s}}^{8} F^{u,s} - W_{RF}^s = W_o^s \tag{17}$$

Institutional restrictions

The Upper Basin water users can use virgin flow available to them within the limits of the share of the Upper Basin water allotted to them after providing the Lower Basin commitment of 8.3 million acre-feet. The quantity available to each state will however vary depending on the three cases of availabilities outlined earlier. Thus, the summation of total consumptive use of water in WRSAs cannot exceed the state's allotment

$$\sum_{s \epsilon y} W_A^s + \sum_{s \epsilon y} W_E^s \leq W^y \qquad y=1, \ldots, 3 \tag{18}$$

where y represents each state. WRSA 1 is in Wyoming, WRSAs 2, 4, 5, 6, and 7 are in Colorado and New Mexico and WRSAs 3 and 8 are in Utah. Further, the annual flow at Lee Ferry (F^L) entering the Lower Basin must be at least 8.3 million acre-feet.

$$F^L \geq 8{,}300{,}000 \tag{19}$$

Water quality

A mass balance approach is used to account for salt outflow (S^{s+1}) from each WRSA and at Lee Ferry. Some salt is taken from the river by both agricultural and energy diversions. Return flow adds salt to the river. The water diverted to energy is assumed to all be consumptively used so that no outflow from the energy sector returns to the river. The pattern of salt movement is thus modeled as

$$S^{s+1} = C_o^s W_o^s - C_o^s W_D^s - C_o^s W_E^s + C_R^s W_{RF}^s$$

or

$$S^{s+1} + C_o^s W_D^s + C_o^s W_E^s - C_R^s W_{RF}^s = C_o^s W_o^s \tag{20}$$

where C_o^s represents the concentration level in the stream flow of WRSA and C_R^s is the return flow concentration.

The salinity concentration resulting from Upper Basin water use is calculated at Lee Ferry, below WRSA 8 (Figure 6). Concentration is the ratio of total salts to water volume at the point of measurement

$$C^L = \frac{S^L}{F^L} \tag{21}$$

where C^L is the concentration level at Lee Ferry, S^L is the accumulated salt from the upper WRSAs to Lee Ferry, and F^L is the volume of flow defined above.

Estimation of C^L from Equation 21 involves a nonlinear relationship which cannot be incorporated within the LP framework. This problem, however, is overcome by using linear approximations of the percentage changes in salt concentration. For the approximations, Equation 21 can be rewritten in general functional form:

$$C = \phi(S, F)$$

The total differential of C is:

$$dC = \frac{\partial \phi}{\partial S} dS + \frac{\partial \phi}{\partial F} dF$$

$$= \frac{1}{F} dS - \frac{S}{F^2} dF$$

$$\frac{1}{C} dC = \frac{F}{S} \cdot \frac{1}{F} dS - \frac{F}{S} \cdot \frac{S}{F^2} dF$$

$$\frac{dC}{C} = \frac{dS}{S} - \frac{dF}{F} \tag{22}$$

Equation 22 states that the percentage change of concentration at any point equals the percentage change of salt less the percentage change of volume of flow. The importance of releasing water for dilution as one means of reducing concentration is easily seen. The smaller the percentage of water depletion ($\frac{dF}{F}$), the greater the flow remaining in the river system, and hence the smaller change in concentration level ($\frac{dC}{C}$).

Specific Models

For determining the allocation of water between agricultural and energy activities maximizing net benefits and the consequent impacts on water quality, 1974 serves as a base year. From this allocation, the change in the salinity level due to projected agricultural and energy usage in 1985 and 2000 can be estimated. If the estimated salinity level exceeds the EPA standard issued in 1974, some control techniques must be undertaken. Control alternatives to reduce salinity include improvement of irrigation efficiency and conveyance systems, irrigation scheduling, desalting irrigation return flows, containment of tail water, utilization of saline flows, flow augmentation through weather modification, and adjustments in water resource allocation and management procedures. Some of these options are not economically feasible, technologically effective, nor politically or legally viable.

Several salinity control techniques have been suggested by the U. S. Department of the Interior (1977) as the most promising for the Upper Colorado Basin. The three important techniques selected for this study are: 1) structural methods of controlling natural sources, 2) irrigation system improvements, and 3) adjustments in water allocation and management of the river. The first option involves construction of evaporation and/or desalting plants at point sources. The second option requires improvement in irrigation efficiency through investment in more water-efficient techniques such as sprinkler systems and lining canals in order to reduce salt loading from return flows. The third option varies the amount of water used for dilution of the salt load of the river. The first two options fall in the category of structural methods whereas the third one is a nonstructural method. In order to analyze the relative effectiveness of structural and nonstructural measures to control salinity, the following four alternative analyses are considered.

Alternative 1

Under this alternative, water is allowed to be transferred freely between uses without consideration of salinity impact. Water will be allocated between agricultural and energy uses such that the value of the marginal physical product of water will be equal in both uses. This allocation is given by the solution to the problem

$$\text{Max } Z_1 = \pi_A + \pi_E$$

subject to Equations 8 through 20 and 22.

The values of Z_1^*, π_A^*, and π_E^* obtained from the optimal solution are of importance for use in the analysis.

Alternative 2

This alternative considers improvement of irrigation efficiency and conveyance systems in addition to construction of evaporation ponds and/or desalting plants (structural alternatives proposed by USBR) for natural point sources as means of reducing salt loading. The expected high salinity levels from future water developments can be reduced through this alternative.

The cost of this alternative is derived as follows: Let C_{SP}^s be the cost per acre of converting to irrigation with a sprinkler system ($X_{i,SP}^s$); C_V^s be the cost per mile of canal lining and V^s be the maximum canal miles in s; and let C_G^s be the cost per ton of salts (G^s) removed by desalting plants and evaporation ponds. The total investment cost of irrigation improvement and construction of ponding for the entire Upper Basin is:

$$TC_I = \sum_{s=1}^{8} C_{SP}^s X_{i,SP}^s + \sum_{s=1}^{8} C_v^s V^s + \sum_{s=1}^{3} C_G^s G^s \qquad i=1, 2, \ldots, H \tag{23}$$

Sprinkler system reduces deep percolation, and canal lining reduces seepage losses. Both methods reduce the amount of salt load entering the river through return flow. Crops can be grown with present irrigation systems (X_i^s and X_p^s) or with sprinkler systems ($X_{i,SP}^s$ and $X_{p,SP}^s$). The productivity of irrigated land under a sprinkler system is assumed to remain the same as under the present system. Although this assumption may not be strictly true, the productivity increases reported are small and data by crop were not available at this time. Hence, the total net return to crops under sprinkler irrigation $\sum_{s=1}^{8} \sum_{i=1}^{H} (P_i^s \delta_i^s - C_i^s) X_{i,SP}^s$ is added to the agricultural net return, π_A'.

The constraints are adjusted to be compatible with the adopted policy by specifying the following equations:

Equation 8 is modified to

$$\sum_{i=1}^{H-1} (X_i^s + X_{i,SP}^s) \leq L_c^s$$

$$X_p^s + X_{p,SP}^s \leq L_p^s \tag{8'}$$

Equation 9 is also modified by adding $X_{i,SP}^{s}$ with the same coefficient values for X_i^s and called (9').

Two additional constraints have the form

$$\sum_{i=1}^{H} \phi_i^s X_{i,SP}^s = W_{A,SP}^s \qquad s=1, \ldots, 8 \qquad (14)+$$

where $W_{A,SP}^s$ is the water consumptive use by crops grown under a sprinkler system. Water return flow resulting with sprinkler systems plus the definition of water consumptive use gives

$$(1 - \alpha_{SP}^s)W_{D,SP}^s - W_{RF,SP}^s = 0$$

$$\alpha_{SP}^s W_{D,SP}^s - W_{A,SP}^s = 0 \qquad (15)+$$

where the symbol α_{SP}^s represents the overall irrigation efficiency of the sprinkler system.

Some water will be lost in desalting plants and evaporation ponds. If W_G represents the amount of water loss per ton of salt removed, the total amount of water loss per projected construction is $W_G G$. The flow-balance Equation 17, the states' water allotment Equation 18, and the salt-balance Equation 20 can be rewritten as:

$$W_{A,SP}^s + W_E^s + W_G^s G^s + F^{s,s+1} - \sum_{\substack{u=1 \\ u>s}}^{8} F^{u,s} - W_{RF}^s - W_{RF,SP}^s = W_o^s \qquad (17)'$$

$$\sum_{s\varepsilon y} (W_A^s + W_{A,SP}^s) + \sum_{s\varepsilon y} W_E^s + \sum_{s\varepsilon y} W_G^s G^s \leq W^y \qquad y=1, 2, \ldots, 3 \qquad (18)'$$

$$S^{s+1} + C_o^s W_D^s + C_o^s W_{D,SP}^s + C_o^s W_E^s + G^s + \mu^s V^s - C_R^s W_{RF}^s - C_R^s W_{RF,SP}^s = C_o^s W_o^s \qquad (20)'$$

The term $\mu^s V^s$ represents total reduction of salt formerly added through seepage from unlined canals. The symbol μ^s is the tons of salt avoided per mile of canal.

Let ΔC^* be the given percentage of salinity reduction that will be achieved through salinity control measures. Hence, Equation 22 is rewritten more specifically as

$$\frac{dS}{S} - \frac{dF}{F} = (\frac{dC}{C} - \Delta C^*) \qquad (22)'$$

The maximization problem for Alternative 2 is formulated as:

$$\text{Max } Z_2 = \pi_A' + \pi_E - TC_I$$

subject to Equations 8', 9', 10 through 16, 14+, 15+, 17', 18', 19, 20' and 22'.

With additional constraints:

$$\pi_A' \geq \pi_A^*$$

$$\pi_E' \geq \pi_E^* \qquad (24)$$

Equation 24 is required to guarantee that the total cost of Alternative 2 comes solely from an investment expenditure.

Alternative 3

This alternative would achieve required water quality levels without investment in structural alternatives by reallocating some water for release for dilution purposes. The cost of this alternative is a diminution of the net return of agricultural and energy production due to a reduction of water consumptive use. The allocation of water to meet a given level of salinity reduction ΔC^* is determined by the following model:

$$\text{Max } Z_3 = \pi_A + \pi_E$$

subject to Equations 8 through 20 and 22'.

Alternative 4

Under this alternative, the salinity level is improved through all available control measures. The cost of this alternative is a combination of investment for irrigation efficiency improvement (both on-farm and conveyance), desalting and ponding, and a diminution of net agricutural and energy returns. The maximization problem for this alternative is

$$\text{Max } Z_4 = \pi_A + \pi_E - TC_I$$

subject to Equations 8', 9', 10 through 16, 14+, 15+, 17', 18', 19, 20' and 22'

The optimization models of Alternatives 2, 3, and 4 will potentially give different optimal levels of agricultural and energy activities than Alternative 1. Furthermore, the best policy will satisfy the two economic criteria:

1. To maintain any given measured quality, the level of each salinity control technique should be such that the quality

improvement achievable by expending an additional dollar is equal for all control methods.

2. The water quality selected should be such that the additional cost for one unit of improvement should be equal to the marginal benefits to the downstream users from that improvement. By this rule, the maximum benefits for the entire river basin are achieved.

The first criterion can be found by comparing the dual variables of Equation 22' of each alternative policy. The dual value of Equation 22' indicates the reduction of maximum joint returns when the water quality standard is increased by one unit.

V. DATA DEVELOPMENT FOR THE AGRICULTURAL SECTOR

Agricultural Land Use and Production

Livestock and livestock products are the major agricultural activity in the Upper Colorado region. Approximately 75 percent of agricultural sales are livestock and livestock products, while sales of field crops, fruits, and vegetables account for 25 percent (U.S. Water Resources Council 1971). Crops in the basin are primarily forage and feed for the livestock industry. Out of 2,208,283 acres of total field croplands in 1974, only 51.8 percent were irrigated. The major crops grown on irrigated land were hay, pasture, corn silage, and small grains. Alfalfa hay and native hay, the main hay crops in the region use about 58 percent of the irrigated land. Pasture and small grains were ranked second and third in acreage of irrigated land. Barley and wheat were the primary grains for feed and brewery. Because of similarities in water consumptive use and irrigation practices, native hay and pasture are aggregated. For modeling purposes, pasture and all hay except alfalfa lands are called pasture land and the rest is called cropland. These lands (shown in Table 11) are used as the base for comparison of future development. The projection of future irrigation development is based on authorized projects as reported by the U. S. Department of the Interior (1977) and presented in Table 4. The new irrigated land is assumed to be used as cropland.

Most of the crops are sold to the local dairy industry and to cattle and sheep ranches. There is some importation of feed for livestock. The annual prices of crops in the four states reported by U. S. Department of Agriculture, Statistical Reporting Service (1974) are shown in Table 13.

The price of corn silage and pasture were not reported. An estimated price of $17.20 per ton of corn silage and $5.19 per animal unit month (AUM) of pasture are used (updated from Willis 1974).

In order to estimate the net return per acre of irrigated land, the productivity (yield per acre) and cost of producing irrigated crops must be presented. Crop yields per acre depend on the type of soil, weather, water, and farm practices. The data for crop yields and cost of production (Tables 14 and 15) are derived from U. S. Water Resources Council (1971), Wright et al. (1972), Davis et al. (1975), and Olsen (1977). Alfalfa hay is divided into alfalfa full and alfalfa partial irrigated. Alfalfa full consumes more water and its yield is higher than alfalfa partial.

The cost data are updated and adjusted to 1974 price levels by using index numbers of prices paid by farmers (Economic Report of the President 1977).

The dollar value of net return per acre of irrigated land is derived by substracting total variable cost from total revenue. This is used as a net return coefficient in the objective function (shown in Table 16). However, the nature of irrigated pasture and the assumption of pasture land in this report made the estimate of net return on pasture land difficult. Irrigated pasture can be under rotation (cropland), permanent (noncropland), or other. All other hay can be either improved or native hay (U.S. Water Resources Council 1971). Alfalfa can be grown separately or mixed with grass and legumes. Native grasses grown on grazing land is widely seen in the Intermountain West. Different pasture types produce different nutritional mixes and result in different net returns when compared with the return on beef production. Properly managed pastures can bring a net return of $25.00 to $164.00 per acre, including credit for labor (Acord 1970). Since pasture land in this study includes all other hay which generally has a higher value than pasture itself, the average net return of $87.35 per acre is selected to represent the net return on pasture.

Table 13. 1974 crop prices (dollars per unit).

Type	Alfalfa hay	All other hay	Barley	Wheat	Oat	Rye	Sorghum grain	Corn grain	Potato
Unit	(ton)	(ton)	(bu)	(bu)	(bu)	(bu)	(hund. wt.)	(bu)	c.w.t.
Colorado	55.50	48.83	2.75	3.80	1.90	2.40	4.75	2.95	3.41
New Mexico	70.00	43.63	2.30	4.00	----	----	5.35	3.20	2.95
Utah	49.50	41.54	2.80	3.97	1.90	-----	----	3.65	3.80
Wyoming	51.50	47.04	2.70	3.96	1.80	2.40	----	3.40	3.20

Table 14. Estimate of annual crop yields per acre of irrigated land.

Subbasin	Alfalfa		Barley	Wheat	Oat	Nurse Crop	Corn		Potato	Pasture
	Ful. (tons)	Par. (tons)	(bu)	(bu)	(bu)	(bu)	gra. (bu)	sil. (tons)	(cwt)	(AUM)
1	3.51	2.73	50	50	50	50	32.4	13.1	87.5	4.5
2	3.22	2.85	50	50	50	50	97.58	15.38	61.1	6.8
3	3.51	3.04	62.5	50	62	50	55.43	12.50	106.3	6.8
4	3.51	3.04	55	50	50	50	99.80	16.44	45.29	6.8
5	3.51	3.04	57	50	50	50	97.58	15.38	145.7	6.8
6	4.15	3.23	62	50	50	50	87.64	17.72	212.38	6.8
7	3.39	2.44	50	50	50	50	87.64	11.80	90.25	6.8
8	3.39	2.44	62.5	50	62	50	--	10.75	156.25	6.8

Table 15. Estimated annual cost of crop production (dollars per acre).

Subbasin	Alfalfa		Barley	Wheat	Oat	Nurse Crop	Corn		Potato	Pasture
	Full	Par.					Gr.	Sil.		
1	72.61	62.89	119.1	73.43	36.70	59.28	43.03	120.61	145.44	11.15
2	74.21	64.27	63.03	73.43	36.70	83.59	93.29	116.32	101.56	13.01
3	68.27	59.13	76.39	73.43	36.70	68.78	82.07	89.10	176.56	13.01
4	74.21	64.27	63.03	73.43	36.70	83.59	95.43	116.32	75.11	13.01
5	74.21	64.27	63.03	73.43	36.70	83.59	93.30	116.32	242.19	13.01
6	102.37	79.67	63.03	73.40	36.70	83.59	83.80	116.32	353.04	13.01
7	81.27	58.49	63.03	73.40	36.70	83.59	83.80	116.32	150.01	13.01
8	65.93	47.46	76.39	73.40	36.70	68.78	-----	89.10	259.73	13.01

Table 16. Net annual return of crops per acre of irrigated land.

Subbasin	Alfalfa		Barley	Wheat	Oat	Nurse Crop	Corn		Potato	Pasture
	Full	Par.					Gr	Sil.		
1	108.14	77.03	119.10	124.57	43.80	25.09	------	------		87.35
2	104.49	93.67	63.03	116.57	58.30	65.38	------	------		87.35
3	105.47	91.35	76.39	125.07	79.20	71.22	136.93	186.10		87.35
4	120.59	104.44	63.03	116.57	65.52	65.38	198.98	166.45		87.35
5	120.59	104.44	63.03	116.57	89.50	65.38	194.56	148.22		87.35
6	127.95	99.59	63.03	116.57	77.30	29.63	174.74	188.46		87.35
7	106.87	76.93	63.03	116.57	61.23	29.63	174.74	158.88		87.35
8	101.86	73.32	76.39	125.07	58.30	71.22	------	186.10		87.35

VI. DATA DEVELOPMENT FOR THE ENERGY SECTOR

Coal

The Upper Colorado River Basin is located in the Rocky Mountain Coal Province. Coal is one of the major energy minerals in the basin. Of the 139 billion tons of coal reserves, bituminous coal accounts for 69 percent, 31 percent is subbituminous, and less than 1 percent is anthracite (U. S. Water Resources Council 1971). Coal deposits in the eight water resources subareas are shown in Figure 7. Coal deposits are found in four major coal bearing regions, and additional deposits are found in other areas.

Hams Fork Region

The Hams Fork Region is located in Western Wyoming. The coal bearing rocks crop out in long narrow belts which are highly folded and thrust faulted. The Bear River, Frontier, and Adaville Formations of Cretaceous age, and the Evanston Formation of Paleocene age, are the major coal-bearing rocks. The region contains four coal fields: Evanston, Kemmerer, Greys River, and McDougal (Glass 1976). The quality of coal ranges between high volatile A bituminous and subbituminous B. Coal deposits up to 20 feet thick occur in the Frontier Formation and are the higher-ranking beds. The Adaville Formation coal is subbituminous in the southern part of the region and bituminous in the north. In the southern half of the region near Kemmerer, Lincoln County, 17 Adaville coal beds exceed 6 feet in thickness and are the best developed in the Kemmerer field. All active mining of this coal is by surface methods.

Green River Region

The Green River Region covers about 15,400 square miles in southwestern Wyoming and extends into Moffat, Routt, and Rio Blanco Counties in northwestern Colorado. Six coal fields in the Wyoming portion are Kindt Basin, Great Divide Basin, Little Snake River, Rock Springs, Henry's Fork, and LaBarge Ridge. Coal ranges in rank from subbituminous C to high volatile C bituminous. The higher rank coals occur on the eastern margins of the region as well as around the Rock Springs uplift. The higher rank coals are of Cretaceous age. Coal-bearing rocks in the Green River Region are largely concealed by younger rocks and very little is known about the total coal resources in the area. Coal beds in the region occur in the Mesaverde Group and the Lance Formation of Upper Cretaceous age, the Fort Union Formation of Paleocene age, and the Wasatch Formation of Eocene age. Coal of the Rock Springs Formation of the Mesaverde has historically been the most important. Coal has been mined in Sweetwater County mainly by underground, and also by surface methods.

In Colorado, coal reserves of this region lie within the Yampa field. The Yampa River, a tributary of the Green River, drains a major part of the area. Most of the coal in this field is of high volatile C bituminous rank (Landis 1959). It contains strippable coal in several beds.

Uinta Region

The coal deposits in this region lie within the boundaries of two structural basins: the Uinta to the west and the Piceance Creek to the east. The coal occurs in the Mesaverde group of Late Cretaceous age and ranges in rank from subbituminous to anthracite. Ninety-four percent of the total is bituminous in rank, mainly high-volatile C. The annual average values per ton of coal in this region are higher than the national average. The Uinta region contains about 3 percent of the nation's original coal reserves (under less than 3,000 feet of overburden). However, historical market conditions have limited production to 1 percent of the total national production (Bureau of Mines 1970). In Utah, 98 percent of the state's coal production has been mined in the Uinta Region (Carbon and Emery Counties), but only 11 percent of Colorado's production comes from this region.

The productive coal fields in Carbon and Emery Counties, Utah, are Castlegate, Sunnyside, and Emery. The Vernal coal field which includes all coal deposits in Uintah County has been mined under poor mining conditions. The Book Cliffs field is located between the Utah-Colorado state line and the Colorado

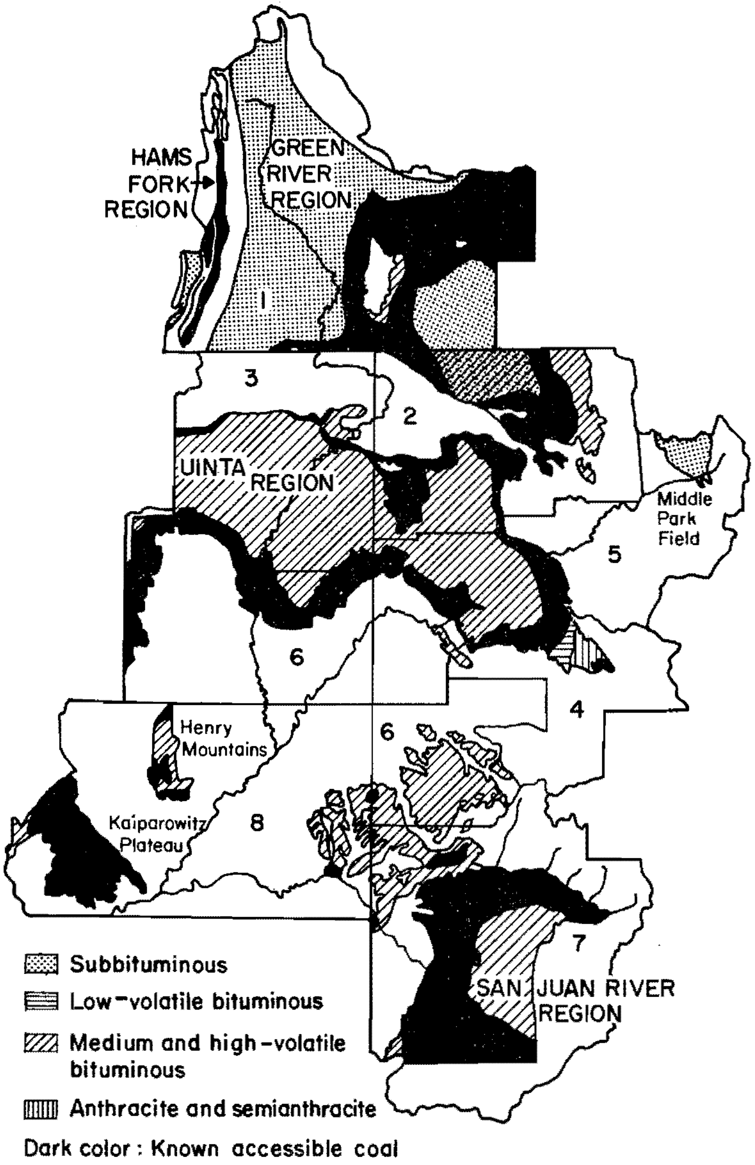

Figure 7. Coal deposits in the Upper Colorado Basin.

River. Seven coal fields located in the Uinta Region portion of Colorado are: Grand Mesa, southern part of the Piceance Creek; Somerset in Delta and Gunnison County and eastern Garfield County; Grand Hogback, between Garfield and Rio Blanco; Danforth Hills, in the northeast flank of the Piceance Creek in Rio Blanco; and the Lower White River field which lies between the Danforth Hills field and the Colorado state line. At present, underground mining is the most amenable recovery method in this region.

San Juan River Region

The San Juan River region comprises the Colorado portion of the San Juan Basin of New Mexico and Colorado. The region is drained by the San Juan River and its tributaries. The coal occurs principally in the Fruitland Formation and in the Menefee Formation of the Mesaverde group. The coal in the region is of high-volatile bituminous rank, with coal of the Menefee Formation generally having a lower ash content than the coal of the Fruitland Formation and Dakota sandstone. The Pagosa Junction district in Archuleta, the Bayfield-Yellowjacket Pass district in Archuleta and La Plata Counties, the Durango field and Red Mesa area in La Plata and Montezuma Counties and the Mesaverde area west of Mesaverde National Park are among major coal areas in the San Juan River region portion of Colorado. The Banker Creek area, the Fruitland area, the Hogback field, the

Navajo field, the Toadlena area, the Newcomb area and portions of Bisti and Chaco Canyon areas are in San Juan County of New Mexico. The strippable coal areas lie along the western and southern part of the basin. San Juan County has large strippable reserves in the Fruitland Formation. The major productive coal areas are the Navajo field and Fruitland areas. In 1970, the Navajo mine, developed at the northern end of the Navajo field, was the largest mine in the United States with production slightly over six million tons (Shomaker et al. 1971). San Juan County, New Mexico, in 1974 produced the most stripped coal of any county in the Upper Colorado River Basin.

Other Coal Areas

Some coal is found in the Dakota sandstone of southwestern Colorado. This coal has lower quality than the coal of the Uinta and San Juan River regions. The major coal areas are the Cortez area in Montezuma, and the Nucla Naturita field in Montrose.

The Middle Park field in Grand County and the Tongue Mesa field in Gunnison, Ouray, and Montrose Counties in Colorado belong to the Denver coal region. The Henry Mountains field in Wayne and Garfield Counties in Utah contains high volatile C bituminous rank coal in a large underground deposit. Construction of Glen Canyon Dam has stimulated exploration and utilization of coal in the Kaiparowits Plateau. The coal is of high volatile bituminous rank and is relatively low in ash and sulfur.

The estimate of the coal reserve base used in this study is the coal resource for which both quality and quantity have been reasonably determined and which is deemed to be mineable at a profit under existing market conditions. After the Environmental Protection Agency established the maximum emission limit of 1.2 pounds of sulfur dioxide per million Btu of heat input, most industrial companies looked for low sulfur and high heat value fossil fuel. Hence, the coal reserve estimated by the Bureau of Mines (1976a) is a more appropriate estimate to use at present market conditions. The reserves are based on measured and indicated coal to a depth of 1,000 feet. By this method of estimation, total coal reserve in the Upper Colorado Basin is nearly 22 billion tons, and strippable coal accounts for 5 billion tons. The coal reserve by County and water resource subarea is presented in Table 17.

Coal in the Upper Colorado River Basin is well suited for electrical power generation, the production of a variety of synthetic petroleum gas products, and such industrial uses as coking for steel production. The locations found to have a mineable coal reserve are shown in Figure 8. The amounts of present and projected extraction are given in Table 18. The values per ton of each are different among locations due to quality and mining methods. These values are presented in Table 19.

In order to estimate the net return per ton of coal in each study area, aggregate prices and costs are used. The extraction cost for each specific mine site is not available; thus, the cost of coal as delivered (f.o.b. prices) to steam-electric plants (Federal Power Commission 1974a and 1976b) is chosen to represent the estimated extraction costs. The net return per ton of coal in this study may be low since "extraction cost" possibly includes normal profit. The average values of coal, cost, and net return per ton of coal are aggregated and shown in Table 20. The average values of underground coals are higher than stripped coals due to quality differential both in heat content as well as sulfur content.

Petroleum and Natural Gas

Total crude oil resources in the Upper Colorado region is estimated at roughly 6.7 billion barrels, of which 0.845 billion barrels are called reserves and nearly 6 billion barrels are predicted additional resources. Total natural gas is estimated to be as much as 103 trillion cubic feet. Approximately 10 trillion cubic feet are estimated as reserves and 93 trillion cubic feet are predicted (U.S. Water Resources Council 1971). The major oil and gas producing areas are located in five basins (Figure 9).

Green River Basin

The Green River Basin is a large sedimentary basin found mostly in Southwestern Wyoming with a thin strip extending into Northeastern Utah along the northern flank of the Uinta Mountains. The field has been a more important source of natural gas than of petroleum (University of Arizona 1971). The field contains four major stratigraphic subdivisions: Cambrian-Permian, Triassic-Jurassic, Cretaceous, and Tertiary. Total future oil and gas predicted (in 1968) are 7,668 million barrels and 24,152 billion cubic feet (Keller and Thomaidis 1971), respectively. Major oil and gas fields are Big Piney-LaBarge and Pinedale in Sublette County; Church Buttes in Uinta; Baxter Basin, Patric Draw, Nitchie Gulch and Wamsutter in Sweetwater; Vermillion Basin, Powder Wash and Cherokee Ridge between Sweetwater and Moffat Counties.

Uinta and Piceance Basins

The Uinta Basin is in the northern part of the Colorado Plateau province in Northeastern Utah. The Piceance Basin is located in Northwestern Colorado. The two basins are rich in hydrocarbons. Commercial production of oil and gas is obtained from strata of the

Table 17. Coal reserves in the Upper Colorado Basin by county (millions of tons).

WRSA	County	Underground	Strip
1	Lincoln	556	1000
	Sweetwater	3625	1116
	Subtotal 1	4181	2116
2	Moffat	2571	270
	Routt	3414	413
	Rio Blanco	1067	0
	Subtotal 2	7052	683
3	Carbon	767	-
	Emery	72	10
	Uintah	40	-
	Subtotal 3	879	10
4	Delta	205	-
	Gunnison	248	-
	Subtotal 4	453	-
5	Garfield (c)	552.99	-
	Mesa	229	-
	Pitkin	88.6	-
	Subtotal 5	870.59	-
6	Grand	-	-
	Montrose	806	60
	Subtotal 6	806	60
7	La Plata	322	-
	Archuleta	66	-
	San Juan (NM)	442	2008
	Subtotal 7	830	2008
8	Garfield	57	24
	Wayne	23	18
	Kane	1715	200
	Subtotal 8	1795	242

Source: Bureau of Mines (1976a), Information Circular 8693.

Paleozoic, Mesozoic, and Cenozoic systems. Estimated ultimate recoverable reserves are in excess of 3.5 billion barrels of oil and 6.5 trillion cubic-feet of gas (Sanborn 1971). Prospects for development of substantial new reserves are excellent. The greater Altamont-Bluebell and Roosevelt Fields in Duchesne and Uintah Counties in Utah, and the Greater Red Wash Field in Uintah County, Utah are the major oil and gas fields in the Uinta Basin. The Greater Altamont-Bluebell Field presently represents the largest producing field in Utah (State of Utah 1976). Rangely oil field and Douglas gas field, located between the two basins, and Piceance Creek gas field are the important fields in Rio Blanco County, Colorado. The Rangely field possesses the largest oil reserve base, accounting for 55 percent of Colorado's total output.

Paradox and San Juan Basins

The Paradox and San Juan Basins are in the Paradox region which covers the area from the San Juan Mountains of Southwestern Colorado to the Canyonlands of Southeastern Utah and the San Rafael Swell in Central Utah. These two areas have good potential for future oil and gas production from Paleozoic rocks. The Paradox region has a cumulative production of approximately 413 million barrels of oil and 5,265 billion cubic feet of gas (Schneider et al. 1971). The Paradox Basin of Southeastern Utah contains sediments up to about 24,000 feet in thickness, but only rocks of Pennsylvanian age have been widely tested. Aneth, Ismay-Flodine Park, and Lisbon are major producing fields in San Juan County of Utah. Most of the oil and gas that have been produced in

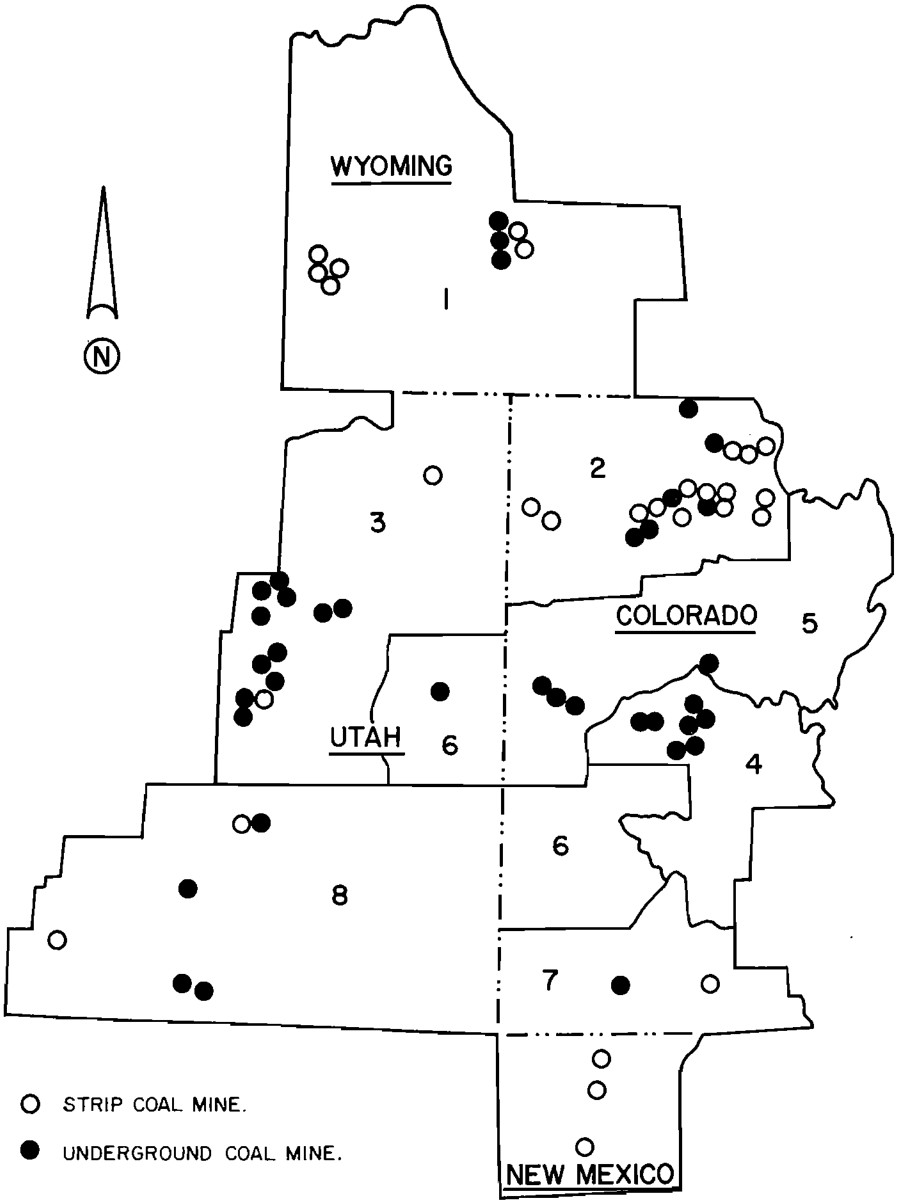

Figure 8. Coal mining activities in Upper Colorado Basin.

the San Juan Basin of Northwestern New Mexico come from reservoir rocks of Pennsylvanian and Cretaceous age. Bisti, Horseshoe, Aztec, Ballard Basin Dakota, Blanco and South Blanco represent important oil and gas fields in San Juan County of New Mexico. Ignacio-Blanco gas field in La Plata County is one major area in Southwestern Colorado.

More details of location of other oil and gas wells can be obtained from publications by the U. S. Water Resource Council (1971) and the American Association of Petroleum Geologists (1971). In 1974 the basin produced oil and natural gas totaling 77.3 million barrels and 638 billion cubic-feet, respectively (Table 21). WRSA 3 was the largest oil producing while WRSA 7 was the largest gas producing areas of the basin.

Data for average prices of crude oil and natural gas were calculated from the reports of the State of Colorado, Oil and Gas Conservation Commission (1974), State of Utah, Division of Oil, Gas, and Mining (1974), the State of Wyoming, Office of Oil and Gas Conservation Commission (1974), and the

Table 18. Coal production in 1974 and projection for 1985 and 2000 (thousands of tons).

WRSA	County	1974 production		1985 production		2000 production	
		Underground	Strip	Underground	Strip	Underground	Strip
1	Lincoln	--	3,353	--	10,800	--	21,600
	Sweetwater	103	735	200+	13,100	58,000	26,200
	Subtotal 1	103	4,088	200	23,900	58,000	47,800
2	Moffat	243	--	2,000+	6,900	44,800	13,800
	Routt	11	3,385	2,300	10,900+	58,800	22,400
	Rio Blanco	12	--	5,500	300	11,000	--
	Subtotal 2	266	3,385	9,800	18,100	114,600	36,200
3	Carbon	2,958	--	11,400	--	43,200	--
	Emery	2,534	--	10,200	500	--	14,900
	Uintah	--	--	--	+	--	--
	Subtotal 3	5,492	--	21,600	500	43,200	14,900
4	Delta	374	--	3,100+	--	6,200	2,100
	Gunnison	891	--	2,600	--	5,200	1,800
	Subtotal 4	1,265	--	5,700	--	11,400	3,900
5	Garfield (C)	1	--	--	--		--
	Mesa	1	--	2,250	--	4,500	1,600
	Pitkin	843	23	1,000	23	2,000	700
	Subtotal 5	845	23	3,250	23	6,500	2,300
6	Grand	--	--	200	--	200	--
	Montrose	--	107	--	107	--	500
	Subtotal 6	--	107	200	107	200	500
7	La Plata	10	--	+	--	40	--
	Archuleta	--	--	--	250	--	500
	San Juan (NM)	--	7,873	--	76,300	--	40
	Subtotal 7	10	7,873	10	76,550	40	540
8	Garfield	--	--	6,000	--		
	Wayne	--	--	10,400	--	53,200	3,000
	Kane	--	--	10,000	1,000		
	Subtotal 8	--	--	26,400	1,000	53,200	3,000
	Grand Total 8	7,981	15,476	67,160	120,180	287,140	109,140

[a] Data from Bureau of Mines 1976, circular 8719 and Mining Informational Services, 1976 Keystone Coal Industry Manual. Production rates of some future mines not specified are indicated by +

Bureau of Mines (1974). Prices vary by oil and gas field. The average prices (total value at wellhead divided by total production) of oil and gas in the basin are shown in Table 22. The estimated drilling costs for oil and gas wells, including dry holes, were obtained from the Federal Energy Administration (1977) and assumed to be uniform over the basin.

Tar Sands

The oil contained in tar sand deposits was formed in the same way as oil found in conventional oil fields. In the United States, tar sand deposits may exceed 30 billion barrels. Most of these are in the Utah portion of the Upper Colorado Basin where individual deposits range from 1 billion to as much as 16 billion barrels (Keith et al. 1978). The majority of tar sand deposits are found in Asphalt Ridge in Uintah County, P. R. Spring between Uintah and Grand Counties, Sunnyside in Carbon County, San Rafael Swell in Emery, Tar Sands Triangle in Garfield and Wayne Counties, and Circle Cliffs in Garfield (Figure 10).

While efforts to recover oil from tar sands have been underway for at least 80 years, there is no commercial production to date in the United States. Several projects have been proposed or initiated to extract oil from tar sands (State of Utah 1976). Sohio Petroleum is conducting a surface mine project in the southern Asphalt Ridge deposit

Table 19. Average value of each per ton (f.o.b. prices) by county and state.

County	Average value (dollars per ton)			State	Average value (dollars per ton)		
	Underground	Surface	Total		Underground	Surface	Total
Lincoln		W		Colorado	13.89	5.33	9.38
Sweetwater	W	W		New Mexico		3.15	3.15
Moffat	W			Utah	12.24		12.24
Routt			5.25	Wyoming	10.19	4.88	5.02
Rio Blanco	9.80						
Carbon	15.66						
Emery	8.73						
Delta	W						
Gunnison	16.03						
Garfield (C)	14.91						
Mesa	9.52						
Pitkin			9.68				
Montrose		W					
La Plata	9.80						
San Juan (NM)		W					

W = Withheld

Table 20. Average price, cost and net return (dollars per ton) of coal production by study area.

WRSA	Underground			Stripped		
	Price	Cost	Net Return	Price	Cost	Net Return
1	5.02[a]	4.06	0.96	5.02	4.06	0.96
2	9.80	7.90	1.90	5.25	4.39	0.86
3	12.24	8.49	3.75	5.25[b]	4.39	0.86
4	14.06	10.50	3.56	-	-	-
5	9.68	7.90	1.78	5.25	4.39	0.86
6	9.38	7.90	1.78	5.25	4.39	0.86
7	9.80	7.90	1.90	5.25	4.39	0.86
8	12.24	8.49	3.75	5.25	4.39	0.86

[a] No data available, state average of total is substituted

[b] At present there is no strip mining in Utah. Data for Colorado is substituted.

7 miles south of Vernal, the U. S. Bureau of Mines has a project in the northwest Asphalt Ridge deposit, and the Oil Development Company of Utah is active in the Tar Sand Triangle deposit.

The only available data on the price and cost of oil production from U. S. tar sands come from the report of the U. S. Congress (1974). That task force study assumed that a world crude oil price of $11 per barrel would be necessary before any significant production of oil from domestic tar sands would occur. The average selling price is estimated at $9.19 (normal development range is from $9 to $10). Average operating costs, including capital depreciation, are estimated at $7.05 per barrel (ranging from $6.66 to $7.88) leaving an average profit of 30 percent. The largest plant expected in the U. S. is 10,000 barrels per day (bpd). Capital investment for such a plant is estimated at $70 million or $7,000 per barrel per day of productive capacity. For the purpose of this study, three 10,000 bpd plants are assumed in Subareas 3, 6, and 8 where production could be started in the year 2000.

Oil Shale

The most important oil shale deposits in the United States are those of the Green River Formation in Colorado, Utah, and

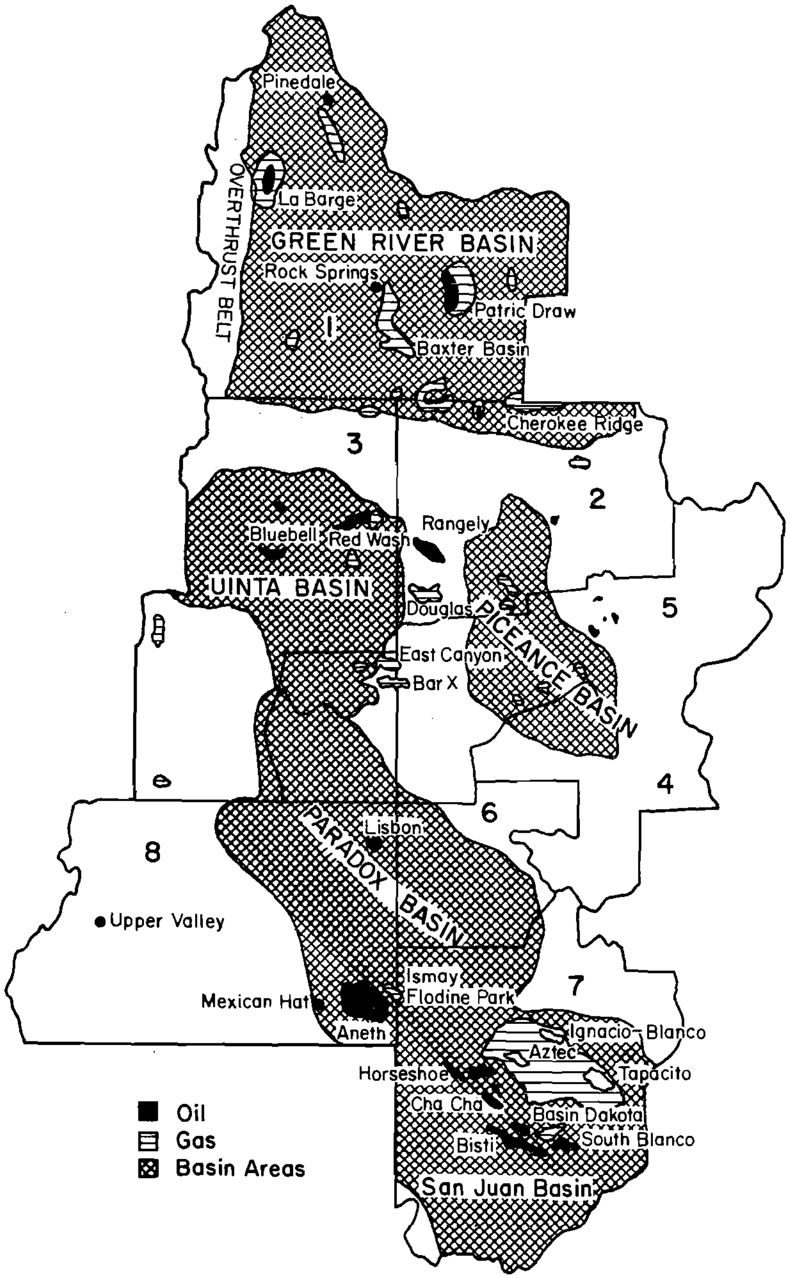

Figure 9. Major oil and gas producing areas.

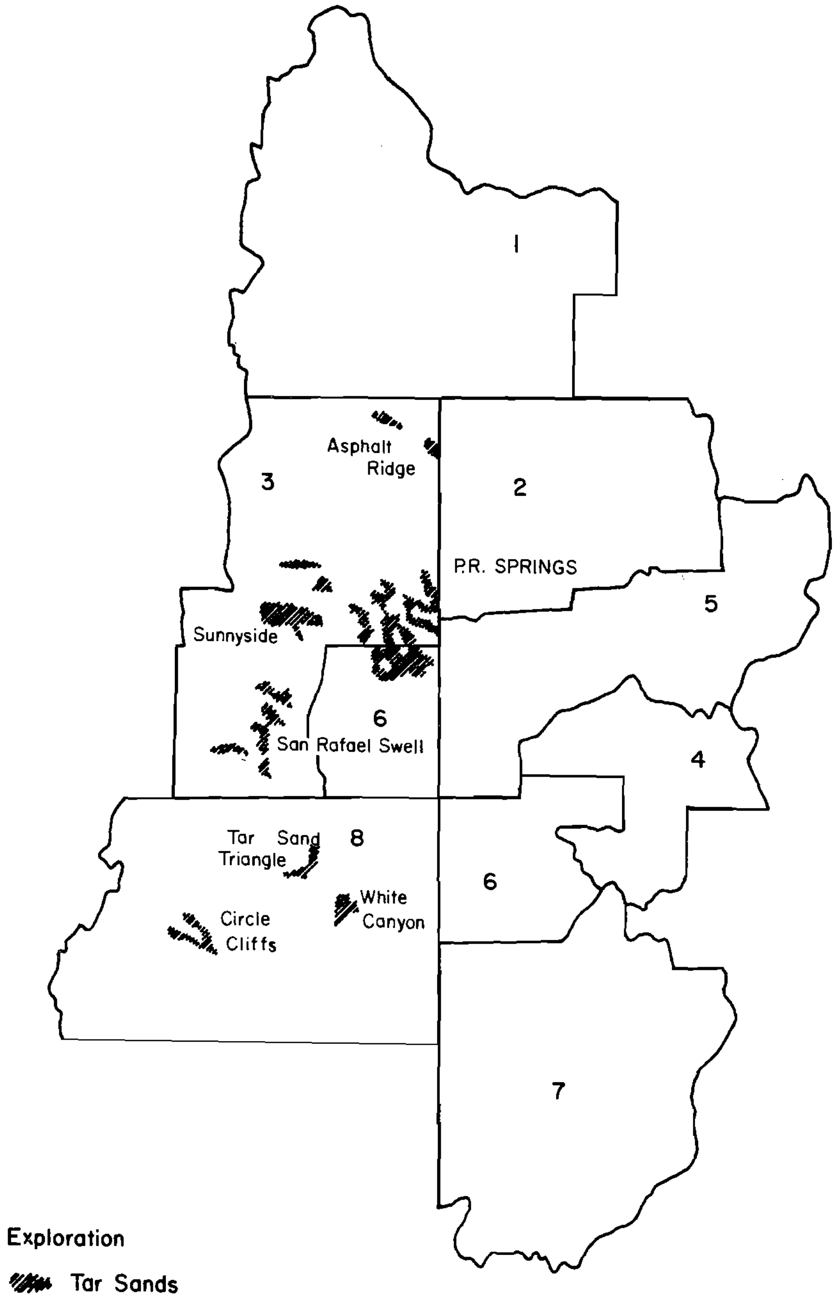

Figure 10. Tar sand deposits.

Table 21. Crude oil and natural gas productions 1976.

WRSA	Crude Oil (bbls)	Natural Gas (mcf)
Sublette	3,456,232	40,117,123
Lincoln	57, 421	3,380,502
Sweetwater	12,496	5,002,930
Uinta	8,047,359	87,936,838
Subtotal 1	11,573,508	136,936,838
Moffat	906,680	24,788,242
Routt	59,432	1,473
Rio Blanco	21,627,533	27,383,429
Subtotal 2	22,593,645	52,173,144
Uintah	4,689,863.9	9,668,002
Duchesne	21,433,704.12	16,957,239
Carbon	1,281.14	395,180
Emery	389.32	5,193,938
Subtotal 3	26,125,238.48	32,214,359
Gunnison	--	--
Hinsdale	--	--
Ouray	--	--
Delta	--	--
Subtotal 4	--	--
Grand	--	--
Summit	--	--
Eagle	--	--
Pitkin	--	421,902
Garfield (C)	--	1,655,766
Mesa	3,284	1,857,118
Subtotal 5	3,284	3,934,786
Delores	325,572	3,744,115
San Miguel		
Montrose		
Grand (U)	84,421.44	5,589,616
Subtotal 6	409,993.44	9,333,731
Archuleta	50,731	23,842
San Juan (C)	240,106	25,950,947
La Plata		
Montezuma		
San Juan (NM)	4,080,000	368,566,000
Subtotal 7	4,370,837	394,540,789
San Juan (U)	10,534,531.54	9,469,415
Wayne	1,705,501.91	--
Garfield		--
Kane		--
Subtotal 8	12,240,033.45	9,469,415
Grand Total	77,316,539.37	638,103,617

Source: Bureau of Mines (1974) Mineral Yearbook, State of Colorado and Utah Department of Natural Resources (1974) and Wyoming Oil and Gas Conservation Commission (1974).

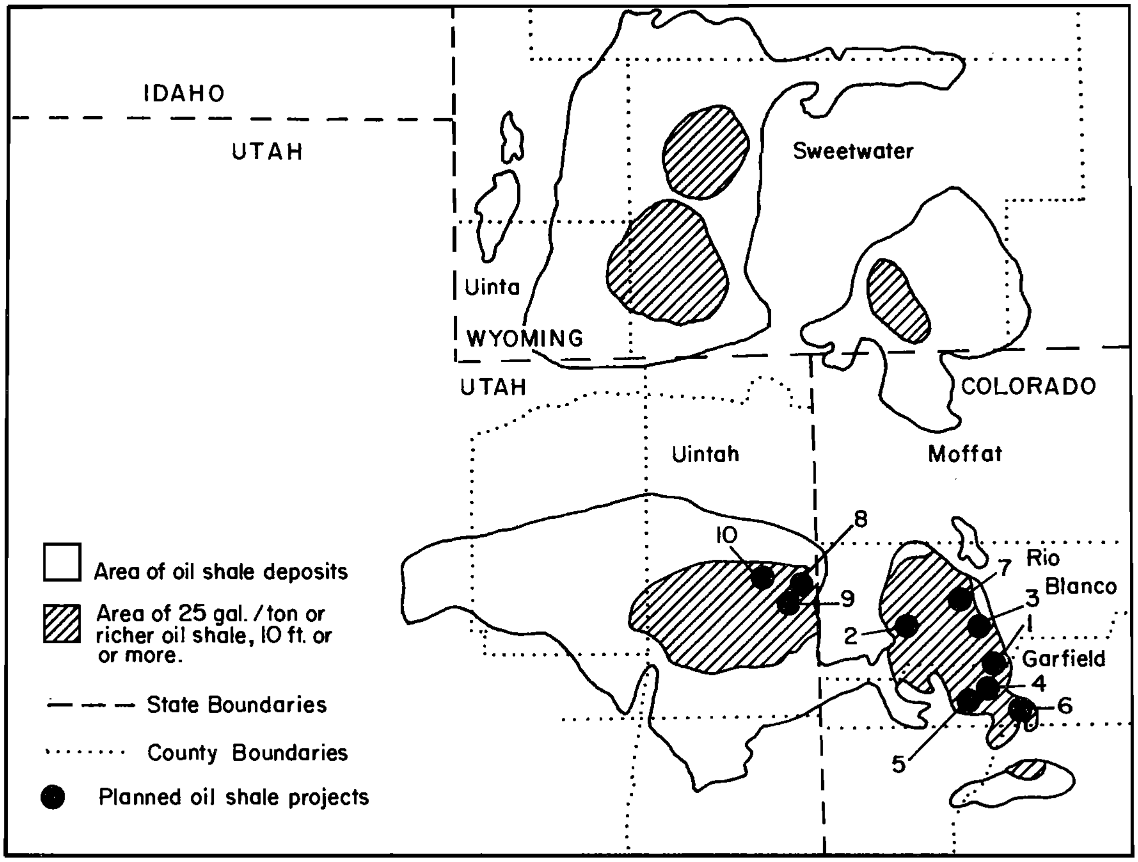

Figure 11. Green River oil shale.

Table 22. Price and estimated cost of crude oil ($/bbl) and natural gas ($/mcf).

WRSA	Price	Cost Oil	Net Return	Price	Cost Natural Gas	Net Return
1	6.53	2.60	3.93	.24	.031	0.21
2	8.20	2.60	5.60	.20	.031	0.17
3	8.26	2.60	5.66	.21	.031	0.18
4	--	--	--	--	--	--
5	8.20	2.60	5.60	.20	.031	0.17
6	8.15	2.60	5.55	.17	.031	0.14
7	7.04	2.60	4.44	.31	.031	0.28
8	5.82	2.60	3.22	.30	.031	0.27

Wyoming (Figure 11). The Green River Formation, which covers about 9,200 square miles in Wyoming, 4,700 square miles in Utah, and 2,600 square miles in Colorado, contains about 1.8 trillion barrels of oil - more than 50 times the total United States reserve of petroleum (Maugh 1977). The 1.8 trillion barrels represent oil in place (total identified shale oil resource in thick, rich beds and medium grade deposits), not recoverable oil. The distribution of shale resources is shown in Table 23. The Parachute Creek Member in the Piceance Basin of Colorado has the richest oil in place.

Based upon economic and technological conditions, only 418 billion barrels in thick sequences (over 100 feet) of high-grade shales (over 30 gallons per ton) are now considered as recoverable reserve. However, according to a recent estimate of the oil in place, using criteria of beds over 10 feet thick averaging over 25 gallons per ton,

Table 23. Identified shale oil resources of Colorado, Utah, and Wyoming (billon) barrells, 42 gallons per barrell).

Grade of Shale	Oil in place Colorado	Utah	Wyoming	Total
Intervals more than 100 feet thick averaging at least 30 gallons of oil per ton.	355	50	13	418
Intervals more than 15 feet thick averaging at least 15 gallons of oil per ton	840	270	290	1400
Totals (rounded)	1200	320	300	1820

Source: U. S. Geological Survey Prof. Paper 820,1973.

Piceance Basin contains 471 billion barrels, Utah 90 billion barrels, and Wyoming 30 billion barrels (Keighan 1975). Thus, the total for the three states comes close to 600 billion barrels.

Oil shale can be mined by surface or underground methods. Both methods begin with a crushing process and are followed by retorting. The three basic methods for aboveground retorting are the ToscoII, the Gas Combustion process, and Union Oil "A" retort. In situ retorting, which follows fracturing the shale underground without mining, has been the subject of a major research and development effort. Projected oil shale mining methods in the Upper Colorado River Basin are shown in Table 24.

The major problem in producing shale oil is the cost compared to other sources of oil. Projected costs have risen rapidly in recent years, partly because of added needs for facilities to comply with air emission standards and for more elaborate solid waste disposal procedures. For these reasons, estimates of the price required to make production economical have become obsolete in a short time (Schramm 1975). Shale oil prices required for profitable production have ranged from about $10 to more than $20 per barrel.

In a study of Synfuels Inter-agency Task Force (1975) shale oil prices of $10.10, $12.70, and $17.94 per barrel, corresponding to return rates of 12, 15, and 20 percent respectively on total investment, were estimated. In another analysis (Whitecombe et al. 1976) based on a detailed design and cost estimate for a commercial oil shale plant (1975 data), the prices required for return rates of 10, 13, and 15 percent on total investment were computed at $14.20, $18.30, and $21.70 per barrel, respectively. The production cost was estimated at $9.91 per barrel at 9 percent interest rate. Using 10 percent DCF return rate at 1974 price levels, the estimated price, cost and net return become $13.00, $9.08, and $3.92, respectively. If world oil prices continue to rise, shale oil may soon be competitive with oil from OPEC and be a significant energy source.

Electricity

Average prices of electricity are calculated by dividing total revenues from sales of electricity by total kilowatt-hour (kwh) sales (Federal Power Commission Report 1974a). Cost data are derived from the appropriate annual reports from the utilities to the Federal Power Commission (1974b). The costs are average production and system expenses incurred by the utilities. The aggregated average price, cost, and net return to utilities in the Upper Colorado River Basin are presented in Table 25.

Synthetic Gas from Coal Gasification

Presently there is no commercial coal gasification in the United States. The "second-generation" processes currently being evaluated at pilot plants may be ready for commercial use sometime after 1980.

It is difficult to determine accurate prices and costs for coal gasification. The price must be competitive with that of natural gas, and it must provide "enough" profit to induce production on a commercial scale. Unless there are government subsidies, the capital investment and operating costs determine the minimum price at which manufactured gas can be sold at the plant site. The cost of coal is the major operating cost. Gasification cost estimates range from $1.00 to $3.00 per million Btu (approximately 1,000 Btu per cubic foot) (Stroup and Thurman 1975, and Lindquist 1977).

The Science and Public Policy Program (University of Oklahoma 1975) estimates

Table 24. Future oil shale projects in Upper Colorado River Basin.

			County	Production (thousand bbl/day)	
				1985	2000
	Colorado				
1.	Parachute Creek	Underground Mine	Garfield, Co.	0	50
2.	Rio Blanco	Open Pit Mine	Rio Blanco	100	100
3.	C-B Project	Underground Mine	Rio Blanco	50	50
4.	Union Oil	Underground Mine	Garfield, Co.	50	50
5.	Roan Creek	Modified in Situ	Garfield, Co.	0	30
6.	Paramo Demonstration	Underground Mine	Garfield, Co.	0	7
7.	Superior Oil	Underground Mine	Rio Blanco	0	68.5
	Utah				
8.	Westco	In situ	Uintah	Pilot	
9.	White River Shale	Underground Mine	Uintah	50	50
10.	Sand Wash	Underground Mine	Uintah	75	75

Note:

The FEA 1985 Scenario calls for a production rate of 300,000 bbl/cd. Apart from the pilot plant the only other proposed plant for producing oil shale that has a stated initial operating date is the Sand Wash plants in Utah, set for 1985. All of the others have indefinite operating dates. We would suggest that for the 1985 date the 300,000 bbl/cd output be split as follows:

State	ASA	
Utah: 100,000 bbl/cd	1401	$220x10^3$
Colorado: 200,000 bbl/cd	1402	$80x10^3$ (Garfield)

In the year 2000 the ERDA 2 Scenario calls for a production of 1,300,000 bbl/cd which far exceeds the $470.5x10^3$ value from the sum of the proposed plant outputs. We suggest that the distribution for the year 2000 be as follows:

State	ASA	
Utah: 450,000 bbl/cd		
Colorado: 650,000 bbl/cd	1401	1.1×10^6
Wyoming: 200,000 bbl/cd	1402	200×10^3

Table 25. Average price and cost of electricity (dollars/mwh).

WRSA	Average Price	Average Cost	Net Revenue
1	16.12	7.08	9.04
2	21.19	7.56	13.63
3	16.12	8.79	7.33
4	-	-	-
5	-	-	-
6	21.71	11.78	9.93
7	21.71	11.78	12.63
8	16.12	8.79	7.33

average costs of $1.02 per thousand cubic feet for Lurgi processes, given a cost of $6 per ton of coal and a hypothetical price of $1.15 per thousand cubic feet for a plant capacity of 2.50 mmcfd. By updating these numbers, the average price of $1.35 and cost $1.21 per thousand feet of coal gas are used for coal gasification production in the basin.

Refined Products From Crude Oil

Cost analysis for refineries is complicated by the fact that several hundred different products may be produced from one basic raw material (i.e., crude oil). The composition of fixed and variable costs will differ in some respects for different oil companies and different products. Russell (1973) has found that crude oil input accounts for over 80 percent of total costs for refineries. The Science and Public Policy Program (1975) estimated a total cost of $334,000 per 1012 Btu per year in operating an oil refinery. Given an approximate value of 6 million Btu/bbl, the average refinery cost becomes $2.00/bbl in 1972 dollars or $2.70/bbl in 1974 dollars (updated by the Nelson operating index for refineries).

The principal products of U. S. refineries are gasoline, jet fuels and kerosene, diesel, and fuel oils. Lubricants, waxes and solvents, petrochemical feedstock, and asphalt (oil) are also produced. The proportions of the principal products vary with refinery design, location, and time of the year. Kolstad (1976) reports the prices of petroleum products in the Rocky Mountain region. The figures for each state in the basin are shown in Table 26.

Using the consumer price index, the petroleum product prices were deflated. The average price of petroleum products, coal and net revenue are estimated in Table 27 for 1974.

Table 26. 1975 prices of petroleum products ($/bbl).

	Oil Products[a] at Refinery	Price Paid[b] by Distributor	Consumer[c] Price
Colorado	12.02	14.63	19.32
New Mexico	11.64	14.41	19.50
Utah	11.74	14.08	18.45
Wyoming	12.08	14.25	19.07

[a] Estimated from regional and national figures

[b] Estimated average for distillate oil, gasoline, and oil for electricity generation

[c] Distributors prices increased by representative gasoline margins from Platt's.

Table 27. 1974 price of petroleum products, cost, and net revenues ($/bbl).

	Price	Cost	Net Revenue
Colorado	16.76	2.70	14.06
New Mexico	16.92	2.70	14.22
Utah	16.01	2.70	13.31
Wyoming	16.54	2.70	13.84

Nuclear Power Industry

The concept of constructing a nuclear power generation complex in the Upper Colorado River Basin is in its infancy. However, the Green River site in Emery County is found capable of sustaining a large (10,000-13,000 mw capacity) nuclear complex (Narayanan 1978). The power produced at the site will be made available to Arizona and California. At present, little is known about plant designs, construction and production costs, and process water requirements.

For the purpose of estimating the production impact on water resources, the existing electricity price in WRSA 3 is chosen to represent the price of this power. Capital expenditures associated with nuclear generating plants are relatively high, but lower fuel costs are considered to make nuclear generation competitive with fossil-fueled plants (National Petroleum Council 1972). Using the average production cost of $8.79 per megawatt-hour of coal-fired electric generating plant, the estimated cost of nuclear power is $7.48 per megawatt-hour, leaving a net return of $8.64 per megawatt-hour.

Energy Conversion Facilities

The output from energy conversion plants such as oil refineries and electricity generating plants are primarily dependent on exogeneous factors such as capital mobility, labor migration, environmental regulations and other institutional factors. Consequently estimates of future production must be very uncertain. For the purpose of this study, the production capacities of various energy conversion facilities at different points in time estimated by Bureau of Mines have been taken to represent maximum capacity. The location of these plants is shown in Figure 12. The capacities for steam electric plants, coal-gasification facilities, oil refineries, and the nuclear plant are shown in Tables 28A, B, C, and D.

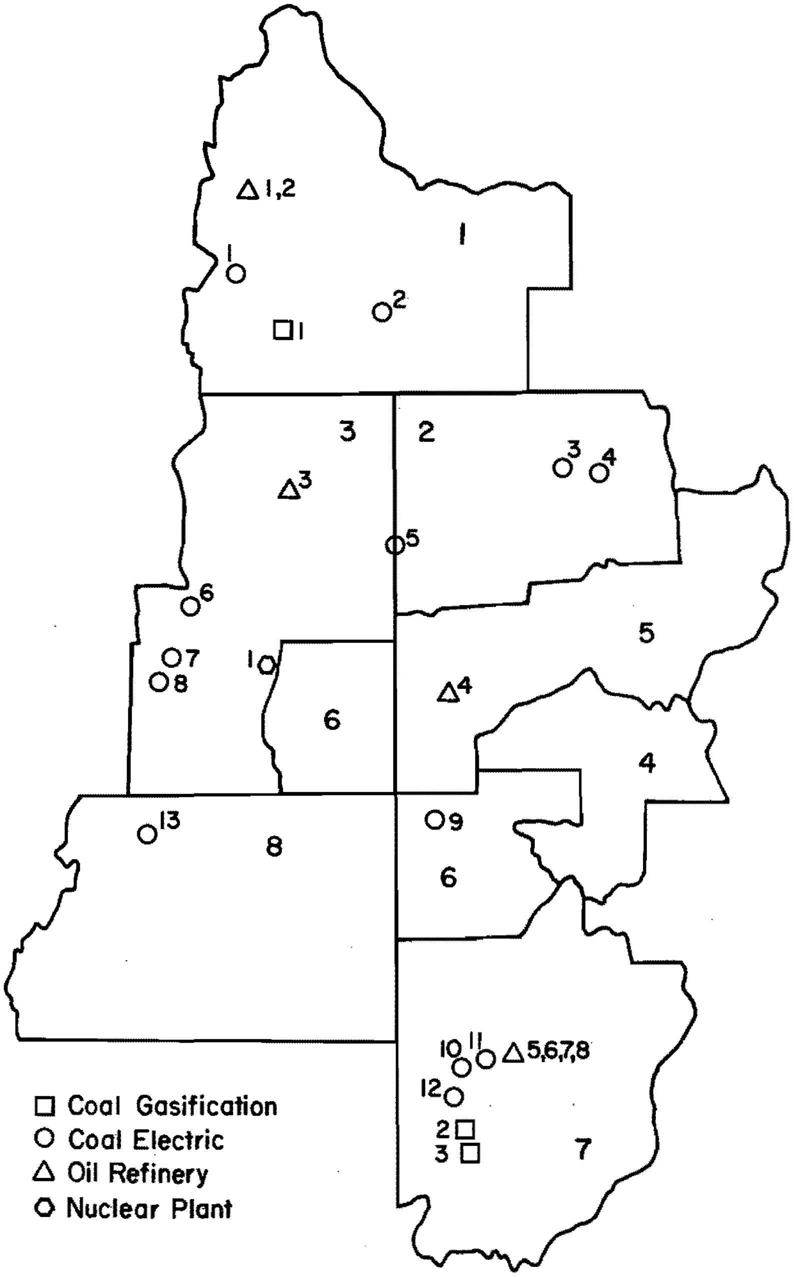

Figure 12. Upper Colorado Basin energy conversion facilities.

Table 28. Capacities of energy conversion facilities.

A Steam-Electric Facilities

Name and Location		Production		MWe
		1974	1985	2000
Naughton 1, 2, 3	Kemmerer, Lincoln County, WY	707.2	1540	1540
Jim Bridger	Rock Springs, WY	560.5	2000	2000
Craig	Craig, Moffat, CO	-	1520	1520
Hayden	Hayden, Routt, CO	163.2	430	430
Hatch Flats	Rangely, Rio Blanco, CO	-	-	300
Carbon 1, 2	Helper, Carbon, UT	188.6	188.6	188.6
Huntington	Huntington, Emery, UT	446.4	1245	1245
Emery	Castle Dale, Emery, UT	-	830	2075
Nucla	Nucla, Montrose, CO	34.5	34.5	34.5
San Juan	Fruitland, San Juan, NM	328.7	328.7	328.7
San Juan	San Juan, San Juan, NM	-	1590	1590
Four Corners	Farmington, San Juan, NM	-	2960	2960
Intermountain	Caineville, Wayne, UT	-	1500	1500

B Coal Gasification Facilities (For 2000 AD only)

Green River	NE Uinta Counta, WY	
Wesco	30 m. SW of Farmington San Juan, NM	250 MMcfd
Burnham	35 m. SW of Farmington San Juan, NM	1,000 MMcfd 785 MMcfd

C Oil Refineries (In Operation)

Mountaineer Refining Co. Inc.	La Barge, Lincoln County, WY	700 bpd
Southwestern Refining Co.	La Barge, Lincoln, WY	500 bpd
Plateau Inc. (Arizona Fuels Corp.)	Roosevelt, Duchesne, UT	7500 bpd
Gary Western Co.	Grand Junction, Mesa, CO	5400 bpd
Thriftway Co.	Bloomfield, San Juan, NM	4020 bpd
Plateau Inc.	Bloomfield, San Juan, NM	7500 bpd
Giant Industries	Bloomfield, San Juan, NM	9000 bpd
Caribou Four Corners, Inc.	Kirtland, San Juan, NM	1500 bpd

D Nuclear Power plant (for 2000 AD only)

Green River	Green River, Emery, UT	13,000 MWe

VII. PREDICTED IMPACTS OF ENERGY DEVELOPMENT

The linear programing model formulated in Section IV was used to predict agricultural and energy development and water usage for several future dates and to analyze the effect of energy development on agriculture in the Upper Colorado River Basin. The first step was to compare 1974 crop production with the production maximizing joint agricultural and energy returns according to the model. As can be seen from the comparison in Table 29, the model predicted the 1974 production of alfalfa, pasture, corn grain, and potatoes better than it predicted the production of small grains and corn silage. The production of intermediate and final coal (Figure 13) and oil (Figure 14) outputs was predicted by location. Coal outputs were sold as raw material or as intermediate input for coal-fired electric power plants. Crude oil was sold as raw material or transported to oil refineries. Natural gas was sold as a raw material at the well.

These agricultural and energy activities were estimated to consume annually approximately 2.026 million acre-feet of water. The predicted consumption by WRSA is given in Table 30. Bishop and Narayanan (1979) estimated the Upper Basin's total consumptive use at 2.161 million acre-feet for irrigation and 0.055 million acre-feet for energy production. These estimates compare favorably with the results of this LP model.

For these levels of production and water use, the model predicted average annual flows of 8.46 million tons of salt and 12.069 million acre-feet of water pass Lee Ferry. This amounts to a concentration of approximately 0.70 tons of salt per acre-foot of water. Historical flow and water quality data show an average of 7.856 million tons of salt and 10.346 million acre-feet of water to pass by Lee Ferry annually. The corresponding concentration is 0.76 tons per acre-foot. The main reason for the discrepancy between the predicted and actual concentration levels is that the salt balance and the flow balance equations do not include several factors which significantly influence the salt concentration. These factors include groundwater movement, climate, vegetation, the snow melt process, and soil moisture effects.

Nevertheless, the match achieved between model results and historical data was considered sufficient to place reasonable confidence in the ability of the model to predict the impact of future economic activities on the salinity concentration. The results will be presented as projections for 1985 and for 2000 under alternative salinity control policies.

Results for 1985

The new area projected to be irrigated by 1985 by already authorized projects amounts to 223,440 acres (Table 4). All of the new lands are assumed to be used as cropland. Almost half of this acreage will be developed in the WRSA 7. There is no projection of new irrigated lands in WRSA 1 or 8.

The increase in energy production in the Upper Basin comes mainly from the proposed new coal mines and electricity plants and from expansions of existing ones. The remainder is expected to come from developing synthetic crude oil from oil shale as a new source of energy supply in the basin. An estimated 300,000 barrels per day will enter the commercial market. Based on these exogenously projected levels of agricultural and energy development, the expected changes in water allocation and the salinity levels were derived from the LP model.

Alternative 1

With this alternative, agricultural and energy activities are developed without any salinity control policies. The model results are given in Table 31. The estimated agricultural net return is $133.88 million. The flows of intermediate and final energy outputs are shown in Figures 15 and 16. Total net return from energy production is approximately $2,615.27 million, with maximum joint net returns of $2,749.15 million. With the increase in agricultural and energy activities, the water consumed is nearly 700,000 acre-feet more than the 1974 level (Table 30 vs. Table 32). The remaining unallocated water is 1.9 million acre-feet. Water consumptive use by state (New Mexico's share is included with Colorado's) is given in Table 33. The greater water consumption and irrigated acreage contributes to a salinity concentration level 9.64 percent higher (an increase of about 50 mg/l) than

Table 29. Actual crop production compared to LP model prediction for 1974 (in acres).

Crop	Actual	LP Model	Discrepancy
Alfalfa Hay	276,851	284,662	(+7,811)
Pasture and other hays	748,029	748,029	(0)
Small grains	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	-

+ and - indicate the LP result discrepancy from actual data.

Table 30. Predicted water consumptive use of agricultural and energy production in 1974 (1,000 acre-feet).

WRSA	AGRICULTURE	ENERGY	TOTAL
1	474.5	17.0	491.5
2	144.0	4.0	148.0
3	310.8	11.4	322.2
4	206.8	0.44	207.24
5	342.9	0.56	343.46
6	233.0	0.44	233.44
7	206.4	6.90	213.30
8	66.9	0.65	67.55
Total	1,985.3	41.39	2,026.69

the 1974 level. The reasons for the increase in concentration are: 1) greater reduction in flow for dilution than the tonnage of salt removed, and 2) more salt washed into the river system by an increase in agricultural activities.

The results bring out the conflict between the allocation of the total quantity of flow among the respective states and the salinity standards for the Colorado River. According to the rules, the Upper Basin water users are allowed to consume Colorado River up to their state share and basin allotment (1948 and 1922 Compacts), but the salinity level at Lee Ferry must be maintained at or below the 1972 level (1974 EPA regulation). The model indicates that when the Upper Basin users continue to develop their compact-apportioned water, the salinity level will increase above the 1972 level. If it is required that salinity be maintained at the 1972 level, the Upper Basin users cannot fully develop their apportioned water unless some additional salinity control effort is made. The projects proposed by the Bureau of

Table 31. Irrigated land in 1985 production (acres).

WRSA	Alfalfa	Pasture	Small Grains	Corn Grains	Corn Silage	Potato	Total
1	39,161	277,231	23,789	-	-	4	340,185
2	30,676	70,516	6,908	-	-	14	108,114
3	71,506	95,047	16,468	-	8,938	11	191,970
4	34,036	82,969	6,807	4,255	-	-	128,067
5	71,802	102,925	14,360	8,975	-	108	198,170
6	76,526	38,053	15,305	-	9,566	2,613	142,063
7	116,624	66,633	25,979	14,578	-	178	223,992
8	14,097	14,655	4,294	-	1,762	112	34,920
Total	454,428	748,029	113,910	27,808	20,266	3,040	1,367,481

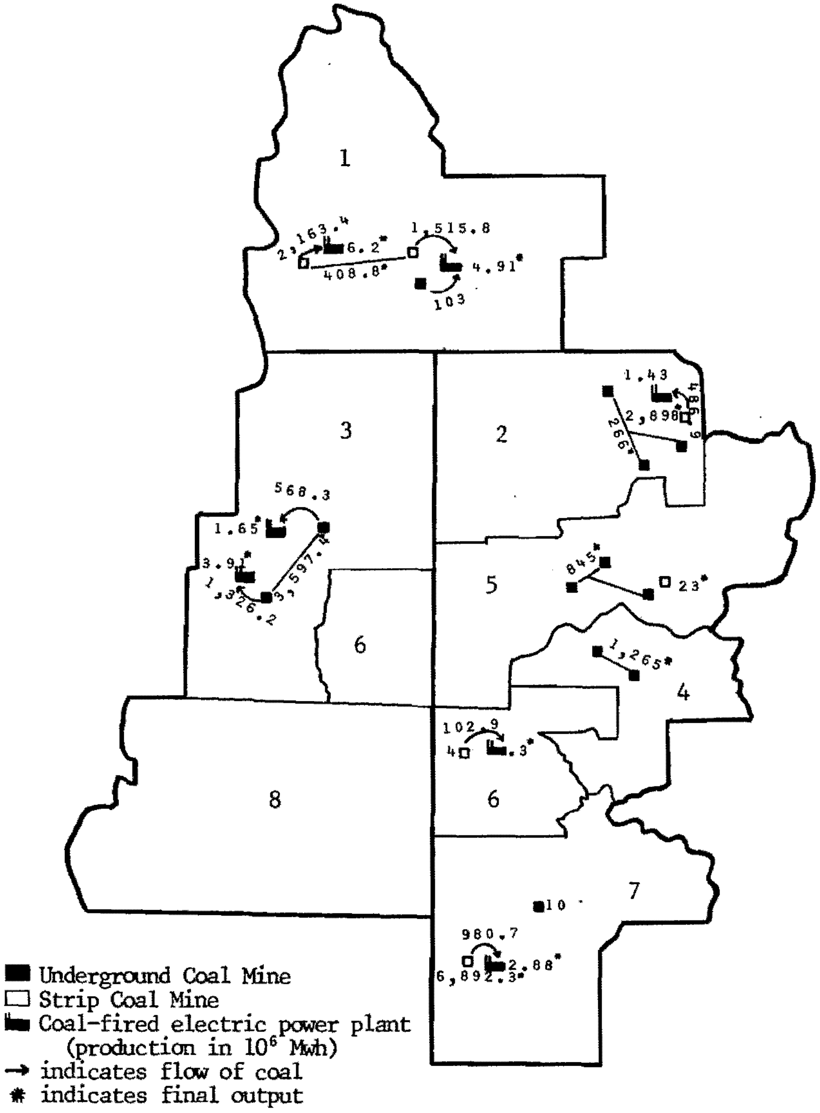

Figure 13. 1974 intermediate and final coal outputs (1,000 tons).

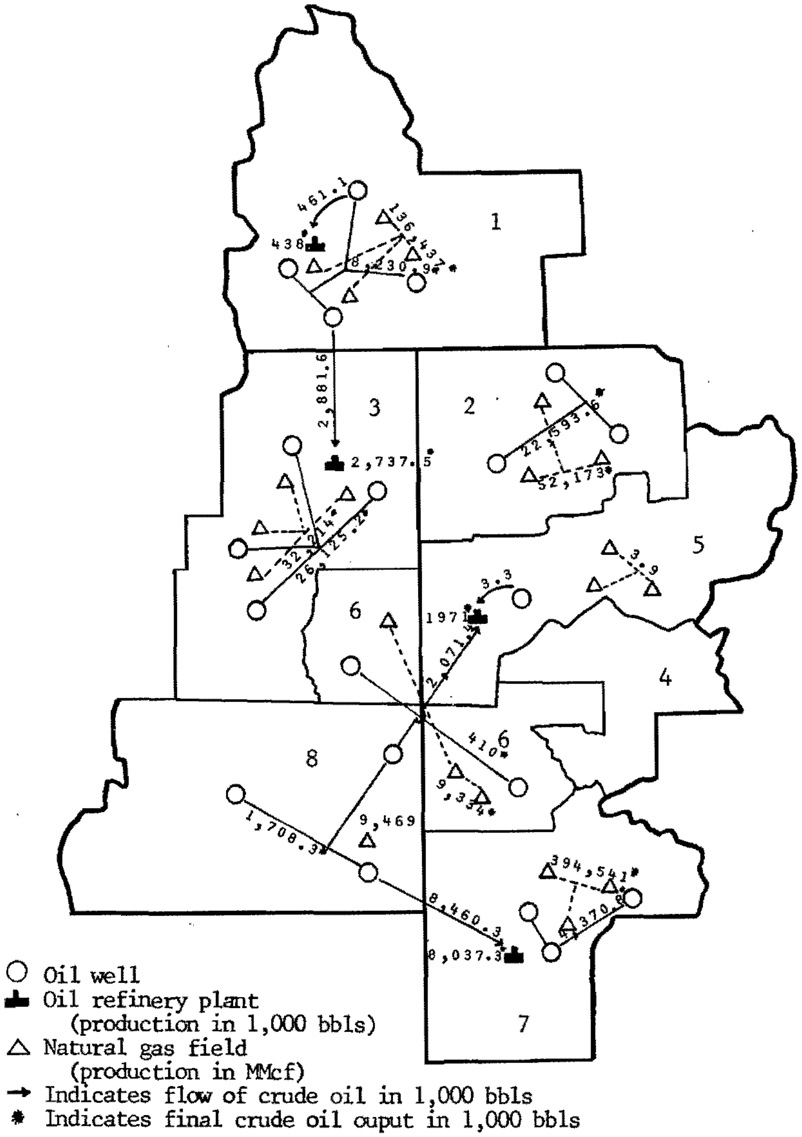

Figure 14. 1974 oil and natural gas production.

Table 32. Agricultural and energy consumptive use of water in 1985 (1,000 acre-feet).

WRSA	AGRICULTURE	ENERGY	TOTAL
1	474.5	48.8	523.3
2	158.6	56.2	214.8
3	360.3	49.4	409.7
4	228.9	2.0	230.9
5	360.4	14.7	375.1
6	350.6	0.51	351.1
7	427.3	76.40	503.7
8	66.9	28.2	95.1
Total	2,427.5	276.21	2,703.7

Reclamation (Table 8) are planned to reduce the salinity level while the Upper Basin states allow water users to increase development and use of water. This policy, as explained in Section II, is inefficient from the economic point of view and involves higher cost to society.

If the EPA firmly enforces its 1974 regulation, it will be necessary to reduce the salinity concentration (C^* indicated in Equation 22') through control measures at an added cost of water development. The results for the levels of effort required to reduce the concentration level by 9.64 percent follow.

Alternative 2

With improvement of irrigation systems and construction of desalting plants and evaporation ponds, the salinity concentration can be reduced by 9.64 percent at an annual cost totaling $14.9 million. This cost comes from: installing sprinkler systems on 95,245 acres of land in WRSA 5; lining 3,487 lineal miles of canal in WRSAs 1, 2, 5, and 7; and construction of a solar evaporation reservoir at the Paradox Valley unit in WRSA 6 (see Table 34). Land under sprinkler systems represents 6.96 percent of total irrigated acreage. Approximately 29.5 percent of canals are lined. Only the Paradox Valley unit, one of the several projects authorized for construction (Table 8) becomes economically feasible. The maximum joint profit for agriculture and energy sectors does not change, but the value of the objective function (Z) is reduced by the amount of the salinity control investment expenditure. Investment funding, either directly by subsidy or cost sharing, is considered a social cost of water quality improvement.

Alternative 3

Another means of reducing the concentration level is through reducing consumptive use of water upstream. The water released from agricultural and energy uses will increase the stream's capacity to dilute salts. However, reduction of water use implies reduction in levels of production. To reduce salinity by 9.64 percent, water consumption must be curtailed by 475.3 thousand acre-feet or 19.6 percent below the Alternative 1 level. The curtailment occurs solely in the agricultural sector (Table 35), and energy production and energy water consumption are not changed from the Alternative 1 solution. Agricultural water consumption is reduced by 1) decreasing the amount of irrigated land, and 2) changing to a crop rotation which is less water intensive. For example, alfalfa can be produced either as a fully or partially irrigated crop. Partial irrigation uses less water but results in a lower yield. According to the model, the minimum foregone agricultural returns to release the water required for salinity dilution amount to $17.4 million. This diminution of agricultural net income is the direct cost to the Upper Basin users of improving water quality. The reduction of marginal lands (pasture) occurs in WRSAs 2 and 5 in the amounts of 22,378 and 102,925 acres, respectively.

Table 33. Agricultural and energy consumptive use of water in 1985 by state (1,000 acre-feet).

State	Total Allotment	Total Consumption	Unconsumed Water
Wyoming	716	523.3	192.7
Colorado	2,813	1,675.6	1,137.4
Utah	1,116	504.8	611.2
Total	4,645	2,703.7	1,941.3

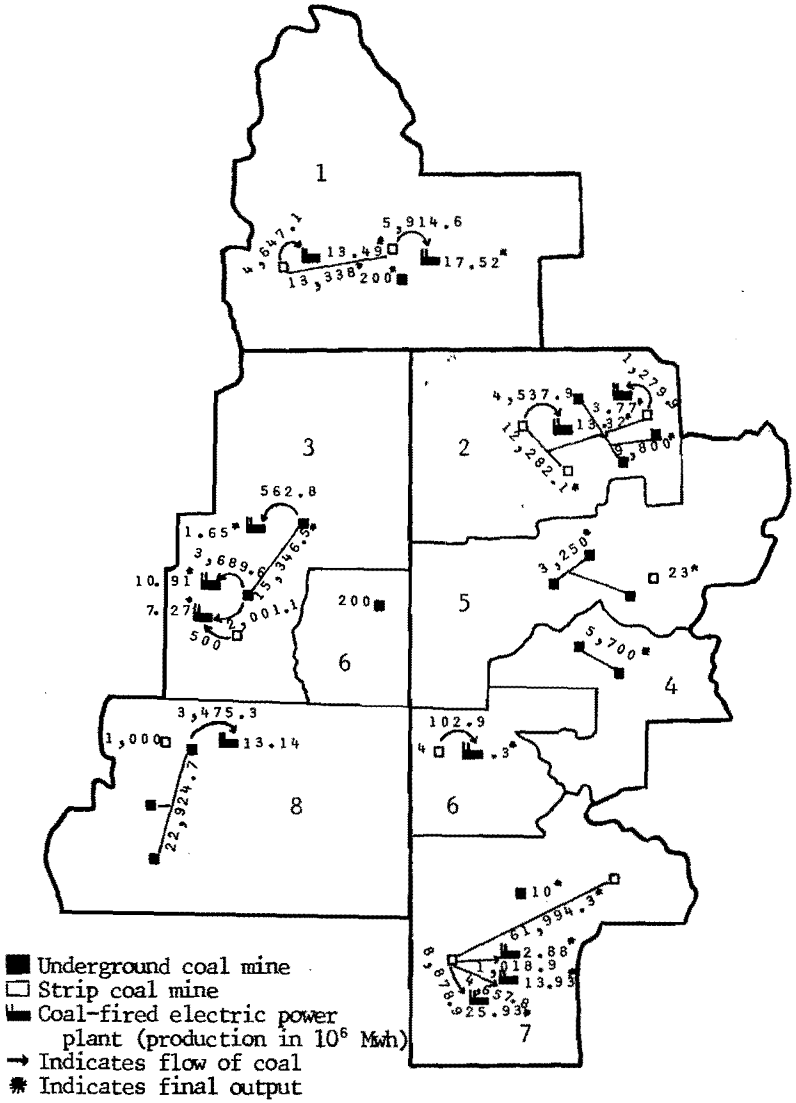

Figure 15. 1985 intermediate and final coal outputs (1,000 tons).

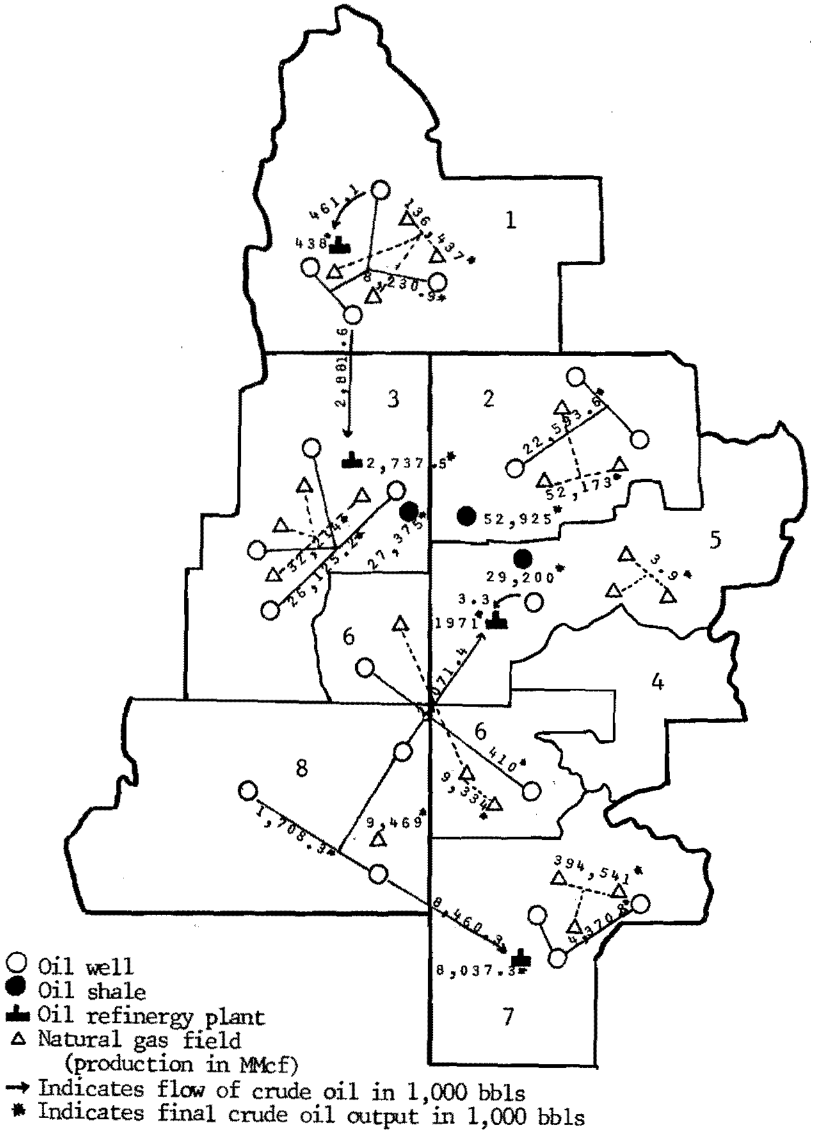

Figure 16. 1985 oil and natural gas production.

Table 34. Salinity control measures of Alternative 2: sprinkler system, canal lining, and ponding.

WRSA	Irrigated Lands Under Sprinkler System (acres)	Lined Canals (miles)	Desalting and Ponding (tons)
1	0	734	0
2	0	708	0
3	0	0	0
4	0	0	0
5	95,245	504	0
6	0	0	180,000
7	0	1,541	0
8	0	0	0
Total	95,245	3,487	180,000
Investment cost	$6.4 M	$6.9 M	$1.6 M

Table 35. Agricultural consumptive use of water in Alternative 3 and the magnitude of reduction as compared to Alternative 1 (1,000 acre-feet).

WRSA	Consumptive Use	Reduction
1	435.3	39.2
2	120.1	38.5
3	360.3	0
4	194.8	34.1
5	113.6	346.8
6	350.6	0
7	310.6	116.7
8	66.9	0
Total	1,952.3	475.3

Table 36. Agricultural consumptive use of water in Alternative 4 and the magnitude of reduction as compared to Alternative 1 (1,000 acre-feet).

WRSA	Consumptive Use	Reduction
1	437.0	37.5
2	158.1	0.5
3	360.3	0
4	228.5	0.4
5	269.9	90.5
6	350.6	0
7	310.6	116.7
8	66.9	0
Total	2,181.9	245.6

Alternative 4

The joint policy, a combination of controlling salt discharges and controlling water use, is introduced as another alternative. Under this alternative, water use is reduced by 245.6 thousand acre-feet through the combination of changes in crop rotations with a shift in alfalfa production to a partial irrigation technology (Table 36). This amount of water reduction is 2.297 thousand acre-feet less than that in Alternative 3. Net return to agriculture is reduced $5.8 million from the level in Alternative 1. Energy production and its allocation pattern, again, is not changed from the Alternative 1 solution. The concentration level is also reduced through a reduction of salt by installing sprinkler systems, lining canals, and building a solar evaporation reservoir (the Paradox Valley unit) (Table 37). The total investment cost is $6.67 million and is added to the agricultural income foregone, making a total of $12.47 million social cost for Alternative 4. The total cost for reducing salinity by 9.64 percent is thus lower under Alternative 4 than under either Alternative 2 or Alternative 3 (Table 38). Under this least cost policy, the marginal cost of reducing the salinity level by 1 mg/l, evaluated at the 1974 salinity level (9.64 percent reduction), is $0.32 million (see Table 38 and Figure 17). Hence, the simultaneous reduction of salt loading through structural techniques and controlling water use results in the minimum cost policy to achieve the given level of water quality improvement.

Table 37. Salinity control measures of Alternative 4: sprinkler system, canal lining, and ponding.

WRSA	Irrigated Lands Under Sprinkler System (acres)	Lined Canal (miles)	Evaporation Pond (tons)
1	0	0	0
2	0	708	0
3	0	0	0
4	0	0	0
5	8,975	0	0
6	0	0	180,000
7	0	1,541	0
8	0	0	0
Total	8,975	2,249	180,000
Investment cost	$.60 M	$4.43 M	$1.64 M

Table 38. Costs of salinity control in 1985 (million dollars).

Control Techniques Costs	Alternative 2	Alternative 3	Alternative 4
Foregone value of output to water use reduction	0	17.4	5.8
Cost of irrigation efficiency improvement and pond construction	14.9	0	6.67
Total cost of maintaining 1974 water quality level	14.9	17.4	12.47
Marginal cost ($M per mg/l)	0.48	0.46	0.32

Benefits of salinity reduction

The Lower Basin water users suffer from an increase in salinity level. To start with the agricultural effects, salinity reduces crop yields, limits the types of crops grown, and requires changes in irrigation practices. Decreased crop yields and growing only salt-tolerant crops (which are generally less profitable) result in direct income losses to farmers. Further, the higher operating and capital expenditures required to irrigate with salty water diminish the net return. Municipal and industrial users (M & I) are affected by higher costs of water treatment, including treatment to reduce water hardness to prolong equipment life. The effects of salinity are also on fish and wildlife, recreation, and the environment. Estimates of direct economic damages are available from several works. Estimated amounts differ depending upon assumptions and methodologies and are:

	Annual damages in dollars per mg/l suffered by Lower Basin		
	Agricultural	M & I	Total
EPA (1971)	$ 45,900	$ 8,790	$ 54,690
Skogerboe and Walker (1972)			150,000
Bureau of Reclamation (1974b)	108,400	121,000	229,400
Valentine (1974)	129,300	124,300	253,600

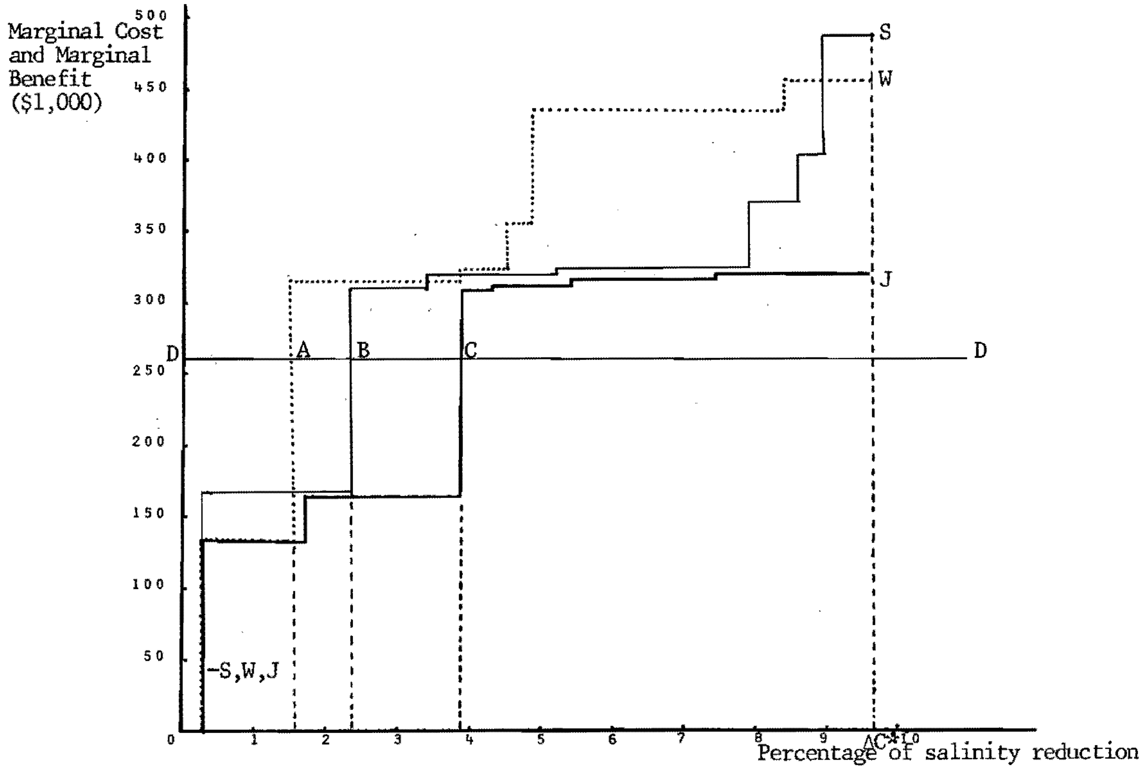

Figure 17. Marginal cost and marginal benefit of salinity control in 1985.

Based on the highest of these three estimates, measures to reduce salinity by 9.64 percent (50 mg/l) would benefit the Lower Basin by reducing damages by $12.68 million. If benefits to Mexico are included in this calculation, total benefits may even be higher. Comparison of this figure with the $12.47 million cost shown on Table 38 shows benefits to the Lower Basin to exceed costs of controlling salinity. This result, however, does not mean that this degree of salinity control can be economically justified. Economic efficiency requires that the net benefits should be maximized. In order to optimize the level of control, one needs to compare marginal benefits with marginal costs. The marginal costs of reducing salinity at that level by these three alternatives are still greater than the marginal benefits which Lower Basin users will receive. The enforcement of the water quality standard (maintaining the 1974 level) is stringent and uneconomical.

If economic criteria are used to set the numeric water quality standard at the 1974 level, the optimal level of water quality improvement will be determined where marginal cost and marginal benefit were equal. To find this optimal level, the marginal cost schedule for each alternative is shown in Figure 17 as constructed by parametrically varying the value of C* (percentage of salinity improvement) in Equation 22'. Schedule SS represents the marginal cost schedule for Alternative 2, WW for Alternative 3, and JJ for Alternative 4, respectively. Schedule JJ shows that Alternative 4 is the minimum cost policy not only at C* (9.64 percent), but at every level of improvement. The line DD represents the marginal benefit (Valentine's estimation) to Lower Basin users which is assumed to be constant. Line DD passes through schedules SS, WW, and JJ at points A, B, and C, respectively. At the points of intersection where marginal benefit of water quality improvement equals marginal cost of each alternative, the level of salinity reductions are: 1.55 percent (7.75 mg/l reduction) by implementing Alternative 3; 2.33 percent (11.65 mg/l reduction) by Alternative 2; and 3.88 percent (19.4 mg/l reduction) by Alternative 4.

The salinity control activities that would comprise an optimal control program are shown in Table 39. WRSA 5, where Grand Valley is located, is most affected by control measures. At the optimal level of salinity improvement, only 71.2 thousand acre-feet reduction of water in WRSA 5 is required for dilution, and only 171,108 tons of salt in WRSA 6 is reduced through the ponding method; to meet the regulatory standard, 245.6 thousand acre-feet of the entire Upper Basin allocation must be saved

Table 39. The level of salinity control activities in 1985 and associated cost at the level where marginal benefit equals marginal cost of improvement.

Policy / WRSA	Alternative 2			Alternative 3		Alternative 4 (Optimal Policy)			
	Land Under Sprinkler System (acres)	Canal Lining (miles)	Ponding (tons)	Water Reduction (1,000 AF)	Land Reduction (acres)	Water Reduction (1,000 AF)	Land Under Sprinkler System (acres)	Canal Lining (miles)	Ponding (tons)
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0.5	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0.4	0	0	0	0	0
5	3,629	0	0	71.8	0	71.2	0	0	0
6	0	0	180,000	0	0	0	0	0	171,108
7	0	0	0	1.2	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
Total	3,629	0	180,000	73.9	0	71.2	0	0	171,108
Total Cost of Implementation	$0.243 M	0	$1.64 M	$1.21 M	0	$1.15 M	0	0	$1.56 M

for dilution and the minimum cost combination of sprinkler installation, canal lining, and evaporation pond construction is used.

The optimal level of improvement is the same when the benefit estimated by the Bureau of Reclamation is used. The optimal level of improvement is lower when the Skogerboe and Walker estimation is applied. Under this estimation, the optimal level of salinity reduction is only 1.75 percent. If the salinity control benefits to Mexico were known, the optimal level might be higher.

Results for 2000

The same methodology was applied to find the impact of agricultural and energy developments on salinity levels for 2000. The projected additional irrigated land from 1985 to 2000 is 9,960 acres, which is considerably less than the rate of increase before 1985. The new energy activities of tar sands extraction, coal gasification, and nuclear power plants are expected to develop around the year 2000.

Alternative 1

The net annual income earned according to the model would reach $133.18 million from agricultural production and $5,598.4 million from energy production. The distribution of crop production is shown in Table 40. Irrigated land would not be fully utilized. In WRSA 1 (an area in Wyoming), transfer of water from agricultural use to energy use occurs through a reduction of 7,057 acres of pasture land. This transfer happens because of a relatively greater expansion of energy development in WRSA 1 than in the rest of the basin (Figures 18 and 19). When water is a scarce resource, it will be transferred from lower valued uses to higher valued uses until maximum returns are obtained. Wyoming's apportioned water would, according to the model, be fully utilized by the expansion of energy development, but part of the apportioned water in other states would be left unconsumed (Table 41). Total energy and agricultural consumptive use of water is 3,248.3 thousand acre-feet, which is 1,221.6 thousand acre-feet greater than the 1974 consumption level. The allocation of water by WRSA is shown in Table 42. Only in WRSA 3

Table 40. Irrigated land in 2000 production (acres).

WRSA	Alfalfa Hay	Pasture	Small Grains	Corn Grain	Corn Silage	Potato	Total
1	39,161	270,174*	23,789	-	-	4	333,128
2	30,676	70,516	6,908	-	-	14	108,114
3	74,751	95,047	17,117	-	9,344	11	196,270
4	33,394	82,969	8,130	4,174	-	-	128,667
5	74,594	102,925	14,919	9,324	-	108	201,870
6	77,553	38,053	15,511	-	9,695	2,613	143,423
7	116,624	66,633	25,979	14,578	-	178	223,992
8	14,097	14,655	4,294	-	1,762	112	34,920
Total	460,850	740,972	116,647	28,076	20,800	3,040	1,370,384

*Reduction of 7,057 acres of pasture land due to water transfer.

Table 41. Agricultural and energy consumptive use of water in the year 2000 by state (1,000 acre-feet).

State	Total Allotment	Total Consumption	Unconsumed Water
Wyoming	542	542	0
Colorado	2,717	1,790.7	926.3
Utah	1,100	915.6	184.4
Total	4,359	3,248.3	1,110.7

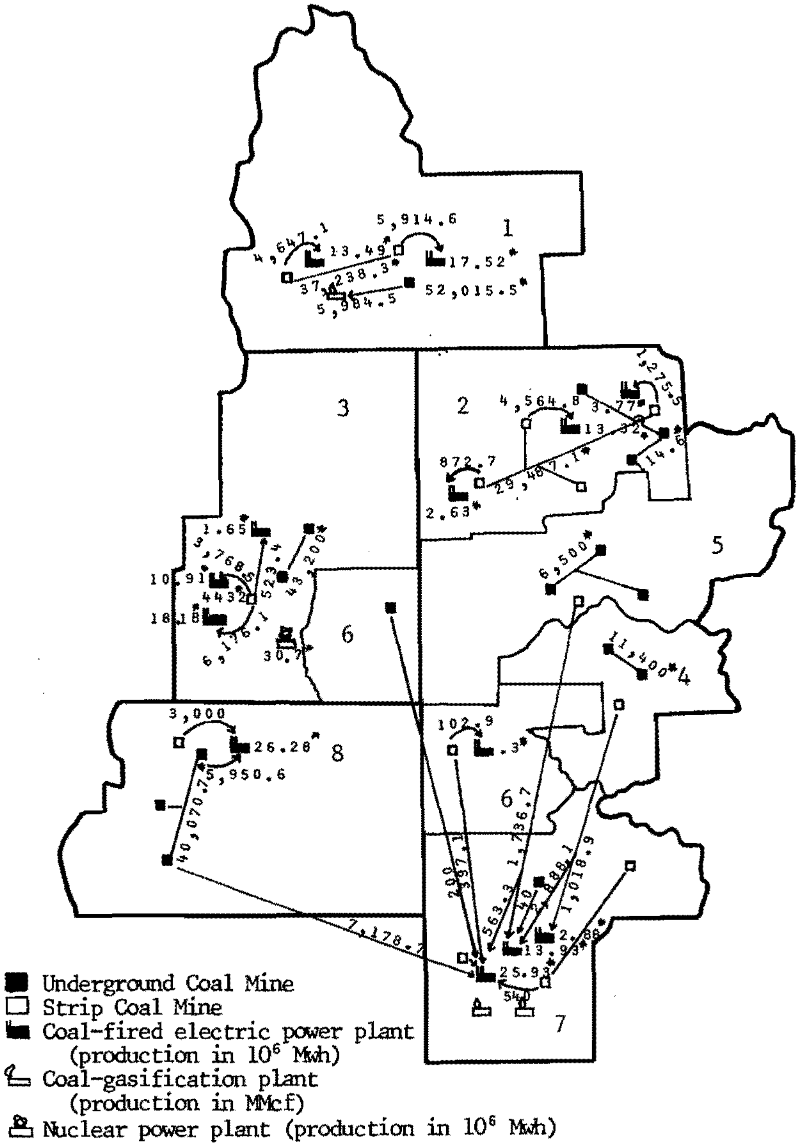

Figure 18. 2000 intermediate and final coal outputs (1,000 short-tons).

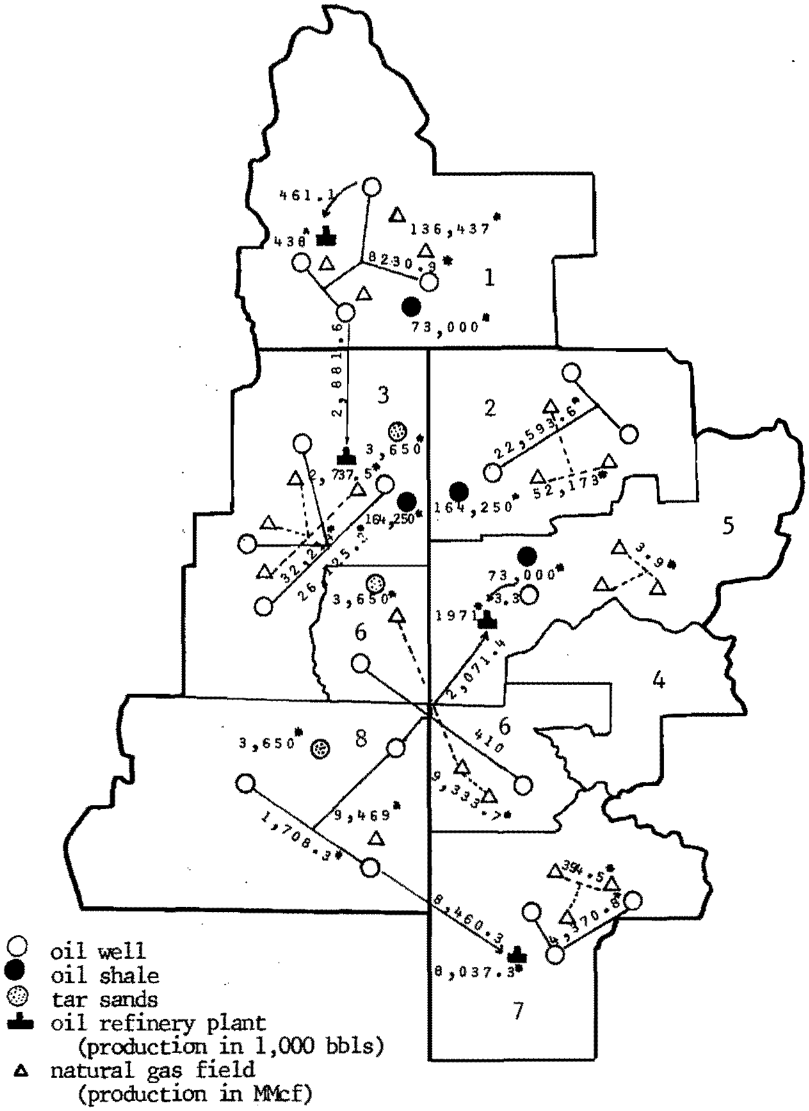

Figure 19. 2000 oil and natural gas production.

Table 42. Agricultural and energy consumptive use of water in year 2000 (1,000 acre-feet).

WRSA	AGRICULTURE	ENERGY	TOTAL
1	426.1	115.9	542.0
2	158.6	150.4	309
3	368.7	423.6	792.3
4	230.1	4.7	234.7
5	367.6	36.3	403.9
6	354.1	.8	354.9
7	427.3	60.9	488.2
8	66.9	56.4	123.3
Total	2,399.0	849.0	3,248.3

(where a nuclear power plant is projected) do energy activities consume more water than agricultural uses. The agricultural and energy water uses increase the salinity level at Lee Ferry by 6.24 percent (approximately 31.2 mg/l) which is less than the projected increase in 1985. The main reasons are: 1) transfer of water to energy reduces the amount of salt returned to the stream by agricultural production, and 2) a relatively greater amount of salt is taken out of the river system by water withdrawal. However, reduction in water available for dilution results in higher concentration than the 1974 level.

Alternative 2

Under this alternative, salt loading is decreased by lining canals for 3,863 miles (32.6 percent of total basin's canals) and by constructing evaporation ponds at Paradox Valley (Table 43). The total investment cost of reducing the salinity concentration level 6.24 percent is $9.24 million. No sprinkler irrigation is installed.

Alternative 3

Water use is reduced by a combination of land retirement in WRSAs 2 and 7 and changes in crop rotation which save water for dilution in the amount of 358.3 thousand acre-feet (Table 43). The diminution of agricultural income resulting from water use reduction is $11.95 million. There is no water reduction in energy uses, and the allocation of energy output is not changed from the Alternative 1 solution.

Alternative 4

The salinity concentration is reduced by a reduction of water use in agricultural production and a combination of lining canals with ponding construction at the Paradox Valley unit. Water use reduction results from changes in crop rotation, mostly from switching fully irrigated alfalfa to partially irrigated alfalfa. Changes in the pattern of crops grown cost the agricultural sector $4.79 million in foregone income; investment on canal lining and pond construction costs $3.3 million. The total cost of implementing this alternative is $8.09 million which is lower than the previous two alternatives (Table 44). The marginal cost of the last mg/l reduction (evaluated at 6.24 percent reduction) is: $0.484 million for Alternative 2, $0.464 million for Alternative 3, and $0.323 million for Alternative 4. Hence, Alternative 4 is, as before, the minimum cost policy to maintain the 1974 level of water quality.

The total benefits of reducing the salinity level by applying each control policy are estimated at $7.9 million. To determine the optimal level of reducing salinity, the marginal cost of each alternative is constructed and shown in Figure 20. Schedules S'S', W'W', and J'J' represent the marginal cost of reducing salinity by 1 mg/l in the year 2000 by implementing Alternative 2, Alternative 3, and Alternative 4, respectively. Line D'D' is the marginal benefit of improving water quality (Valentine's estimation); it passes through marginal cost levels S'S', W'W', and J'J' at points D, E, and F, respectively. At each intersection point, at which the values of marginal cost and marginal benefit are equal, the level of water quality improvement is determined. The improvement level is 2.52 percent (12.6 mg/l reduction) by implementing Alternative 2, 1.36 percent (6.8 mg/l reduction) by Alternative 3, and 3.49 percent (17.45 mg/l reduction) by Alternative 4. The salinity control activities and associated costs at the level where marginal benefit equals marginal cost are given in Table 45.

Policy Implications

The model has shown the importance of water management in reducing the salinity level. If water management for dilution purposes is ignored, then structural methods (i.e., canal lining, sprinkler system, and ponding) to reduce salt loading are unnecessarily costly. The optimal salinity control program involves reducing both water usage and salt loading simultaneously in the Upper Colorado River Basin.

Policy instruments to affect salt loading and water usage

To be effective, each policy instrument must be effectively designed to reduce salinity. Policy instruments must be administratively and economically efficient in order to obtain the maximum social welfare for the entire basin, and they should also consider equity issues for water users.

Table 43. The level of salinity control activities in 2000 for maintaining salinity at the 1974 level.

Policy / WRSA	Alternative 2			Alternative 3		Alternative 4			
	Land Under Sprinkler System (acres)	Canal Lining (miles)	Ponding (tons)	Water Reduction (1,000 AF)	Land Reduction (acres)	Water Reduction (1,000 AF)	Land Under Sprinkler System (acres)	Canal Lining (miles)	Ponding (tons)
1	0	734	0	0	0	0	0	0	0
2	0	708	0	120.4	70,516	.5	0	708	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	34.6	0	1.2	0	0	0
5	0	880	0	74.6	0	74.6	0	0	0
6	0	0	180,000	0	0	0	0	0	180,000
7	0	1,541	0	128.7	6,012	116.7	0	137	0
8	0	0	0	0	0	0	0	0	0
Total	0	3,863	180,000	358.3	76,528	193.0	0	845	180,000

Table 44. Costs of salinity control in 2000 (in million dollars).

Control Techniques Costs	Alternative 2	Alternative 3	Alternative 4
Foregone value of output to water use reduction	0	11.95	4.79
Cost of irrigation efficiency improvement and pond construction	9.24	0	3.30
Total cost of maintaining 1974 water quality level	9.24	11.95	8.09
Marginal Cost ($M per mg/l)	0.484	0.464	0.323

Under Public Law 95-217, pollution from irrigation runoff is not subject to the National Pollutant Discharge Elimination System (NPDES) permit. Because of the high cost of monitoring waste discharges from many farms, regulation by using effluent standards and a tax system is not practical. Private incentives to invest in measures that would reduce salt loadings or consumptive use, however beneficial they may be in terms of social welfare, will not exist unless the increment of private benefits exceeds the increment of private costs.

Investments in conveyance systems (under the Water Systems Improvement (WSI) Project) and in evaporation ponds are currently proposed for the Colorado River Water Quality Improvement Program, which is financed by federal appropriation (Public Law 93-320). Investments in sprinkler systems to reduce return flows and consequent salt loading is another alternative. Farmers will adopt sprinkler systems only when they expect the benefits (increasing crop yields or reducing water cost) received from these systems to be greater than the costs they pay

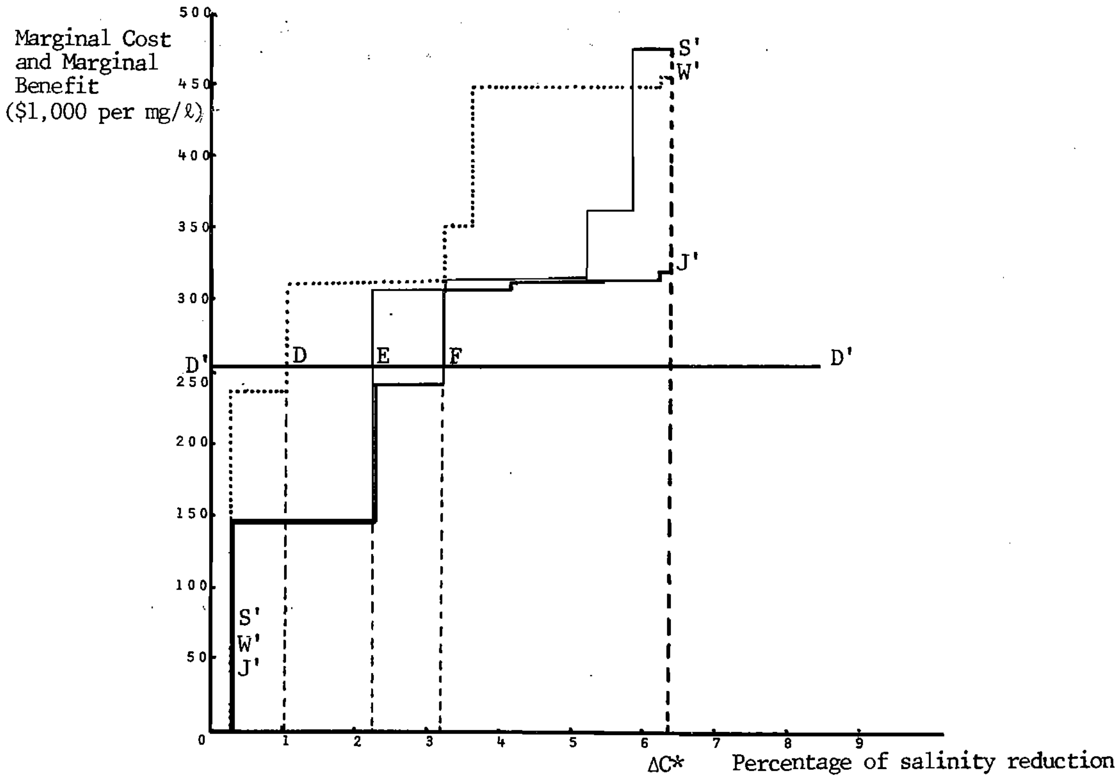

Figure 20. Marginal cost and marginal benefit of salinity control.

Table 45. The level of salinity control activities in 2000, and their associated costs at the level where marginal benefit equals marginal cost.

Policy	Alternative 2			Alternative 3		Alternative 4 (Optimal Policy)			
WRSA	Land Under Sprinkler System (acres)	Canal Lining (miles)	Ponding (tons)	Water Reduction (1,000 AF)	Land Reduction (acres)	Water Reduction (1,000 AF)	Land Under Sprinkler System (acres)	Canal Lining (miles)	Ponding (tons)
1	0	0	0	0	0	0	0	0	0
2	0	50	0	0.5	0	0.5	0	40	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0.5	0	1.6	0	0	0
5	0	0	0	74.6	0	74.6	0	0	0
6	0	0	180,000	0	0	0	0	0	180,000
7	0	0	0	1.0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
Total	0	50	180,000	76.6	0	76.7	0	40	180,000
Total cost of Implementation (million dollars)	0	0.098	1.64	1.25	0	1.30	0	0.078	1.64

for installation. Analysis done at Utah State University (1975) indicates that the farmers' investment cost is likely to exceed the benefit received. One way to still make sprinklers attractive to farmers would be to subsidize the difference between the cost and benefits to farmers as an incentive for them to install sprinkler systems. Other policy instruments, to be discussed later, can also be used.

The direct regulation of consumptive use to reserve river flow for dilution purposes is considered impractical and politically infeasible. This kind of regulation would necessitate a major change in institutional structure in order to bring the consideration of water quality to the determination of individual water rights and interstate water divisions. The major political problem would be that the reduction of water consumptive use implies a direct reduction of the Upper Basin water users' income to the benefit of the Lower Basin users.

Taxing water users by increasing the price of water has been mentioned as one of the policy instruments to reduce water use. Under an elastic demand for irrigation water (Andersen and Keith 1977), a relatively small increase in the price of water, other things being equal, will induce water users to reduce relatively large quantities of consumption. But unfortunately, this is impractical under the present water rights and water allotment laws. A totally utilized fixed supply of water allocated between the Upper and Lower Basins by law, results in a perfectly inelastic supply of water faced by Upper Basin users. Therefore, a tax on water use does not in general reduce the amount of water consumed.

The most promising way to reduce water consumptive use and salt loading effects is by the creation of a market for water rights. Howe and Orr (1974) propose a water rights purchase program (WRPP) in which some regional agencies stand ready to purchase all water rights offered to them at a price set through bargaining among willing sellers and willing buyers. Under this competitive basis, the prices will reflect an opportunity cost of water for the water users. The advantages of Howe and Orr's proposal are:

1) The water rights acquired can be resold for higher-valued uses within the system. Water transfers from agricultural uses to energy uses will help reduce the salt loading effect (providing there is zero discharge from energy uses) as shown earlier in the result of Alternative 1 for the year 2000.

2) If the price is high enough, the farmer will have an incentive to sell some portions of his water rights to other users. He could then make do with a lesser amount by changing irrigation practices to divert less water, installing sprinkler systems, or lining canals. The benefits from (1) and (2) come primarily from a reduction of salt loading rather than a reduction of water consumptive use.

3) A farmer will reduce his consumptive use when the marginal benefits of selling 1 acre-foot of water are equal to or greater than the marginal benefit of using that acre-foot of water in growing crops. The farmer himself decides whether to abandon irrigated lands or to substitute crops requiring less water.

Another advantage of this proposal is that the location for operating this program is flexible. It should be located where the salinity problem is most critical. The WRPP is a nonstructural method for improving water quality; it can be used to induce socially efficient private decisions regarding water and salinity management. Also, it is operational under present state water laws and compacts.

This LP model is able to indicate where and at which level the WRPP and structural methods of improving salinity levels should be put into action. At the optimal combination of control measures, two control variables are simultaneously determined: the amount of water that must be saved for dilution purposes, and the level of construction for ponding, canal lining, and sprinkler systems at specific locations for salt loading reduction. This LP model is capable of aiding the Colorado River authorities in making policy decisions on water resources allocation and salinity management within an integrated framework for the benefit of society.

CONCLUSIONS

Potential energy development in the Upper Colorado River Basin will increase the demand for water over time. The increased water demand will cause reallocation of the ownership of water rights. Associated with the change in water use and the increased water consumption, salinity levels are predicted to increase by 10 percent in year 1985 and then decrease to only 6 percent above present levels by the year 2000 at Lee Ferry. The marginal cost of controlling salinity to comply with EPA recommended standards was found to be $320,000 per milligram per liter for 1985 projected agricultural and energy development. The corresponding cost for controlling salinity through proposed structural measures was $480,000 and through only nonstructural measures was $460,000 (Table 38). This indicates the importance of the so-called "dilution solution" in reducing the cost of salinity control.

The marginal cost of controlling salinity for the Upper Basin is greater than the marginal benefits from the improved quality for downstream users at the 1972 salinity levels. Therefore, the standard is too stringent from the economic efficiency point of view. From that point of view, the standard should be relaxed by roughly 6 percent in year 1985 and by 4 percent in year 2000.

Among the proposed structural measures, the Paradox Valley unit is feasible under all conditions. Other projects are found relatively ineffective. Improvements in irrigation efficiency through investments in sprinkler systems and canal lining in certain areas such as Grand Valley seem to be quite effective. Relatively small percentages of water should be held for dilution purposes in areas where the salinity problems from irrigation return flows are severe. This policy will reduce the cost of salinity control by $1.6 million per year for the 1985 scenario and about $1.2 million per year for the 2000 scenario as compared to the pure structural alternatives.

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Appendix A

Convexity of an Isoprofit Function

Assumptions
1) Water is owned by firm one and two with fixed quantity.
2) Water is the only input in firm one's and firm two's production.
3) Firm one and two are in perfect competition in the output market.
4) Firm one and two are profit-maximizers.
5) Each production function has neoclassical production properties.

Let X_1 and X_2 be an output of firm one and two respectively

$$X_1 = f(W_1)$$

$$X_2 = g(W_2)$$

where W_1 and W_2 are water used in the production. Assumption 5 implies

$\frac{\partial X_1}{\partial W_2} = f'(W_1) > 0$ and $\frac{\partial^2 X_1}{\partial W_2^2} = f''(W_1) < 0$;

similarly

$\frac{\partial X_2}{\partial X_2} = g'(W_2) > 0$ and $\frac{\partial^2 X_2}{\partial W_2^2} = g''(W_2) < 0$.

If Px_1 and Px_2 are the price of X_1 and X_2 respectively, and there is no cost of using water, the joint profit (Π) of two firms can be written as

$$\begin{aligned} \Pi &= Px_1 X_1 + Px_2 X_2 \\ &= Px_1 f(W_1) + Px_2 g(W_2) \end{aligned}$$

If the joint profit is held constant at some certain level, the rate of change between W_1 and W_2 is found by differentiating the joint profit function

$$d\Pi = Px_1 f'(W_1)\, dw_1 + Px_2 g'(W_2)\, dW_2$$

Since $d\Pi = 0$,

$$\begin{aligned} \frac{dW_2}{dW_1} &= - \frac{Px_1 f'(W_1)}{Px_2 g'(W_2)} \\ &= - \frac{VMP_1}{VMP_2} < 0 \end{aligned}$$

The negative ratio of $\frac{dW_2}{dW_1}$ implies the negative slope of an isoprofit function. The rate of change of $\frac{dW_2}{dW_1}$ can be examined by finding the second derivative of $\frac{dW_2}{dW_1}$

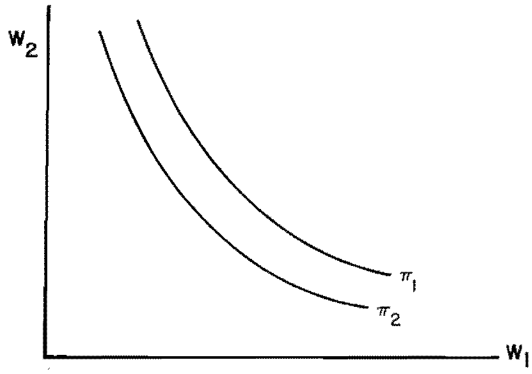
$$\frac{d^2W_2}{dW_1^{\,2}} = - \left[\frac{(VMP_2(Px_1 f''(W_1)) - VMP_1(Px_2 \cdot g''(W_2) \frac{dW_2)}{dW_1}}{(VMP_2)^2} \right]$$

$$= - \left[Px_1 \cdot f''(W_1) \frac{VMP_2}{(VMP_2)^2} - Px_2 \cdot g''(W_2) \frac{VMP_1}{(VMP_2)^2} \cdot \left(- \frac{VMP_1}{VMP_2}\right) \right]$$

$$= - \left[Px_1 \cdot f''(W_1) \frac{VMP_2}{(VMP_2)^2} + \frac{Px_2 \cdot g''(W_2)}{(VMP_2)^3} \cdot (VMP_1)^2 \right]$$

$$\frac{d^2W_2}{dW_1^{\,2}} = - \left[\frac{Px_1 \cdot f''(W_1)\ (VMP_2)^2 + Px_2 \cdot g''(W_2)\ (VMP_1)^2}{(VMP_2)^3} \right] > 0$$

The negative value of the rate of change of W_1 and W_2 and the positive value of the rate of change of $\frac{dW_2}{dW_1}$ means that the slope of an isoprofit function is negative and increasing (Chiang, 1974, pp. 254-255). Thus, the shape of the isoprofit function is convex to the origin. The higher the isoprofit curve, the higher the joint profit of firm one and two.



Appendix B

Concavity of Water Quality Standard Constraint

For a two firm model, a water quality stream standard equation can be written as

$$\frac{C_0W_0 - C_0W_1 - C_0W_2 + S_1 + C_nW_n}{W_0 - W_1 - W_2 + W_n} = \overline{C}$$

where W_0 and W_n represent the quantity of natural flow and natural inflow respectively. C_0 and C_n are the natural flow and natural inflow concentrations. Thus, C_0W_1 and C_0W_2 are the salt that is taken out from the river system by firm one and two respectively $\overline{C}$ is a given level of concentration downstream. S_1 is the salt discharge and is assumed to be an increasing function of water consumptive use (Rhoades et al. 1974).

$$S_1 = S_1(W_1)$$

and $\frac{\partial S_1}{\partial W_1} > 0$. The rate of the rate of change in salt discharge respect to water consumptive use is also assumed to be increased at increasing rate, i.e. $\frac{\partial^2 S_1}{\partial W_1^2} > 0$. Substituting S_1 into the water quality stream standard equation

$$\frac{C_0W_0 - C_0W_1 - C_0W_2 + S_1(W_1) + C_nW_n}{W_0 - W_1 - W_2 + W_n} = \overline{C}$$

Rearranging the terms

$$C_0W_0 - C_0W_1 - C_0W_2 + S_1(W_1) + C_nW_n = \overline{C}(W_0 - W_1 - W_2 + W_n)$$

$$(\overline{C}-C_0)W_2 = (\overline{C}-C_0)W_0 + (\overline{C}-C_0)W_n - (\overline{C}-C_0)W_1 - S_1(W_1)$$

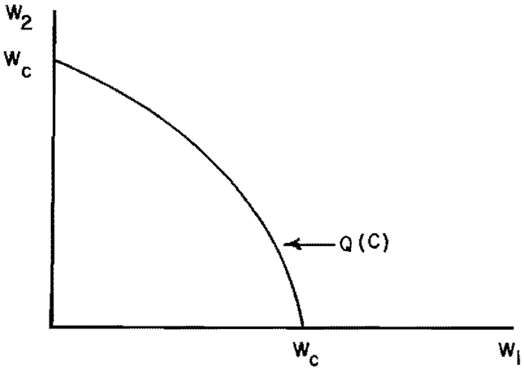
$$W_2 = \frac{(\overline{C}-C_0)(W_0+W_n)}{(\overline{C}-C_0)} - \frac{(\overline{C}-C_0)W_1}{(\overline{C}-C_0)} - \frac{S_1(W_1)}{(\overline{C}-C_0)}$$

$$\frac{dW_2}{dW_1} = -1 - \frac{1}{(\overline{C}-C_0)} S_1'(W_1) \quad 0$$

$$\text{where } S_1'(W_1) = \frac{\partial S_1(W_1)}{\partial W_1}$$

$$\text{and } \frac{d^2W_2}{dW_1^2} = -\frac{1}{(\overline{C}-C_0)} S_1''(W_1) < 0$$

$$\text{where } S_1''(W_1) = \frac{\partial^2 S_1(W_1)}{\partial W_1^2}$$



Let Q(C) be called the water quality standard curve. It shows the relationship of W_1 and W_2 at a certain level of quality. The slope of Q(C) is negative and decreasing. In order to maintain the water quality level, an increase in the use of water by firm one must result in a decrease in the use of water by firm two at the decreasing rate, and vice versa.