Effects of Energy Development in the Upper Colorado Basin on Irrigated Agriculture and Salinity

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A mathematical programming model is formulated to determine the salinity impacts of energy development in the Upper Colorado River Basin. Using this model, the costs and benefits to Upper and Lower Basins in complying with the 1974 EPA regulations on numerical salinity standards are examined. Optimal water quality levels consistent with economic criteria are established for projected energy growth in the basin. The efficiency costs and equity implications of the salinity regulations are analyzed.

The Upper Colorado River Basin, with its vast energy resources, is faced with large-scale development which will substantially increase the demand for water. Given the arid environment and the strong agricultural base of the region, changes in water allocation as a result of this increased demand and the concomitant impacts on water quality are of serious concern for the entire basin. Several studies have been conducted to estimate water availability for energy production based on a water requirements approach [Water for Energy Management Team (1974), Goslin (1975), Hansen (1976)]. To evaluate water quality impacts of energy development, results from simulation models with certain envisioned scenarios have been used [Utah State University (1975), Bishop (1977), Andersen and Keith (1977)]. These studies indicate that water is a scarce resource in the basin and that the changes in water allocation will have significant impacts on the salinity of the river. The approaches used by these studies for allocating water resources to the emerging energy industries are rather arbitrary. Further, discrete management alternatives used by these studies based on a simulation framework to control salt concentrations tend to overestimate the cost of salinity measures in the basin.

The objectives of this paper are to a) analyze water allocation based on economic theory using an optimization framework; b) evaluate the cost of complying with the decisions of the EPA Enforcement Conference on the Pollution of Interstate Water of the Colorado River; c) determine the "economically optimum" water quality level and the means of achieving it; and d) evaluate the equity considerations implied by the recommendations of the EPA Conference.

Water Quality Effects of Energy Development

Numerous studies have been conducted on the water quality of the Colorado River and particularly the salinity problem [Hyatt, et al.; Howe and Orr (1974b); Utah State University; Gardner and Stewart; and Young]. Salinity control measures are necessary to comply with the Mexican Treaty (Minute No.

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242) as well as to resolve the externality problem posed among the Upper and Lower Basin users. The 1972 EPA Conference, which included the Seven Basin State Representatives and the EPA, recommended that the salt concentrations should be maintained at or below the 1972 levels in the lower mainstem. Further, the conference concluded that for implementation purposes, salinity must be treated as a basinwide problem that needs to be solved if Lower Basin salinity is to be maintained at or below 1972 levels while the Upper Basin develops its share of the Colorado River waters. With the enactment of PL92-500, the EPA required that basin states set numerical standards for salinity on the Colorado River. In response, the Colorado River Basin Salinity Control Forum was formed. This body provided the necessary interstate cooperation for the promulgation of the 1974 regulations on Colorado River salinity, and for establishing water quality standards and Plans of Implementation.

Anticipated energy development in the Upper Basin adds another dimension to the problem. Operations such as surface mining, which expose fresh geologic material to the atmosphere will contribute additional salt to surface and subsurface runoff due to the high level of natural salts in the alluvial soil. Another potential increase in salinity due to energy development stems from the "salt concentrating effect" which depends on (a) the wastewater disposal decisions of the energy sector and (b) the spatial allocation of water in the basin. With the implementation of PL92-500 and PL95-217 (which seek to control both point and non-point sources) and the EPA's goal to achieve elimination of discharge (EOD) by 1985, wastewater from energy production will not likely be discharged but will be contained in evaporation ponds [Keith,]. Therefore, appropriation of the presently unused or uncommitted water for energy production could increase downstream salinity concentration, as a result of water depletions that would have otherwise served to dilute the salt entering the river [Bishop].

If no further allocation is made for energy production from the Colorado River System, water rights will have to be purchased from other users. Since the marginal product of water in agriculture is estimated to be lower than in energy, intersectoral transfer of water can be expected [Andersen and Keith]. This shift could result in improved water quality due to possible reduction in additional salt loading from irrigation return flows. The magnitude of the change in salinity in the lower mainstem of the Colorado River will depend on how and where the energy sector acquires its water rights.

Economic Aspects of Salinity Control

It is well recognized that the salinity problem should be viewed as a basinwide problem and treated as such in advocating policies for resolution. Yet, the relationships between institutions involved with water allocation decisions and those with water quality management responsibilities are not generally recognized or clearly understood. Consequently, water resource development and allocation decisions are likely to proceed independent of water quality considerations. In fact, the Colorado River System Implementation Plan provides for the development of the entire compact-apportioned waters in the Upper Basin while maintaining present salinity levels in the Lower Basin. The plan thus ignores the possibility of providing dilution. Consequently, increased structural alternatives to control salinity are likely to be pursued. In addition, the users contributing to the salt loading of the river will be penalized excessively since dilution as an alternative to reduce salinity is not recognized. In particular, the agricultural sector, which is estimated to contribute 30 percent of the salt loading, will bear a relatively larger burden than is economically optimal.

In order to resolve this issue and provide economic criteria for salinity management, two rules should be followed. First, to maintain any given numeric quality, the level of each salinity control technique should be

chosen so that the quality improvement achievable by expending an additional dollar for each control measure is the same. Secondly, the water quality should be maintained such that the additional cost of increasing the water quality by one unit should be equal to the marginal benefits to the downstream users from that increment of quality. The first rule only indicates the cost-minimizing combination of alternative techniques to achieve a given quality level, whereas the second statement indicates the maximization of benefits achievable for the entire River Basin.

The first step of the analysis is the selection of control techniques. Some of the alternatives to reduce salinity include improvement of irrigation efficiency and conveyance systems through structural alternatives, irrigation scheduling, desalting irrigation return flows, containment of saline tail water, utilization of saline flows, flow augmentation through weather modification, and dilution through appropriate water allocation. These options may not all be economically feasible, technologically effective, or politically and legally viable.

The two control measures that seem most promising in the near term are a) providing dilution through water allocation mechanisms, and b) improving irrigation efficiency which reduces additional salt pickup in the return flows. The first option is concerned with the extent to which water can be allocated for different uses in a given location so that dilution of the salt loading can be accomplished consistent with output maximization in the region. The second option considers investments in improving efficiency in order to reduce salt loading from irrigation return flows such that overall investment costs are minimized.

One rationale for adopting dilution as a policy for controlling salinity is that allocation decisions are yet to be made and the decision makers can be well informed about the impact of alternate allocations on salinity before large-scale development occurs. The efficiency improvement option is vigorously pursued in many parts of the basin with federal subsidy and would be of use in determining how extensive a program may be required for controlling salinity. Although not explicitly stated, Howe and Orr (1974a) utilize the same control measures in theoretically demonstrating their Water Repurchase Program for salinity control.

Description of the Optimization Framework

The Upper Colorado River Basin constitutes the southern part of Wyoming, western Colorado, eastern Utah and the northwestern part of New Mexico. The study area was subdivided into eight water resources subareas (WRSA) as shown in Figure 1. A two-sector linear programming model consisting of agriculture and probable energy activities in the basin was formulated. The four submodels contained in this formulation were the agricultural production model, the energy production model, the water resources model, and the salinity model.

Agricultural activities included production of alfalfa, small grains, corn silage, potatoes, and pasture. Net returns to agriculture were defined as the proceeds from sale of final outputs less total variable costs. Necessary data were obtained from U.S. Department of Agriculture (1974), Acord, Wright et al., Davis et al. and Olson. The relevant constraints for this submodel were the present and potential availability of different classes of irrigable lands [U.S. Department of Commerce (1974), U.S. Department of the Interior (1977)] and various crop rotations.

The energy submodel included production, conversion and transportation of energy materials. Specifically, the activities considered were production of crude oil, natural gas, oil-shale, petroleum refining, surface and underground mining of coal, coal-fired electric power generation, and coal slurry. The net returns to the energy sector were defined as the gross revenue from the sale of final energy outputs less the costs of extraction, conversion and inter-regional transpor-

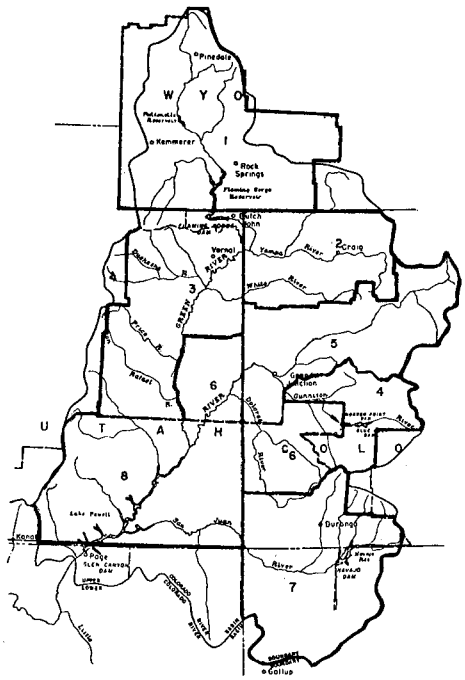

Figure 1. Water resources subareas for the upper Colorado River basin.

tation. The relevant constraints for this submodel included inter-regional energy flows, resource availabilities and plant capacities of the conversion facilities. The necessary data were obtained from the Minerals Yearbook by U.S. Department of the Interior (1974), Bureau of Mines Information Circulars 8682A and 8689 by the U.S. Department of the Interior (1975, 1976), Federal Power Commission Reports (1974), and several Oil and Gas Commission Reports by States. Documentation of all the data sources can be found in a recent dissertation by Padungchai.

The water resource model consisted of a set of constraints that restricted the use of water in agriculture and in energy to be less than or equal to the net availability of water in each basin less fixed requirements for other uses such as municipal, wetlands and transbasin diversions [U.S. Water Resources Council (1971, 1976, 1977) and Christiansen]. Further, the total consumptive use of each state was limited by the Colorado River Basin Compact amounts. Assuming an average virgin flow of 15 MAF and a downstream commitment of 8.3 MAF (which includes 7.5 MAF for the Lower Basin, 0.75 MAF for Mexico and 0.05 MAF for Arizona), the rest was allocated between Colorado, New Mexico, Wyoming and Utah such that the individual state shares would be no more than 51.75, 11.25, 23.0 and 14.0 percent respectively as dictated by the compact.

The salinity model was based on a mass-balance approach. The total natural salt inflows into any given WRSA were first calculated. The amount of salt removed with water depletions for all uses was subtracted from this quantity. The additional salt loadings from the irrigation return flows were then added to determine the total salt contribution for each WRSA. These were sequentially added to give the total salt loading at Lees Ferry. The necessary data for this part of the model were obtained from Utah State University, Hyatt et al. and U.S. Department of Interior (1974 and 1977).

Both outflows of water and salt at Lees Ferry were variables determined within the model. The constraint on the concentration

of salt at any point can be set by letting the ratio of the outflow of salt to water be less than or equal to a desired level. This constraint can be expressed as a linear inequality for a given level of concentration by appropriately rearranging terms. However, there are two difficulties with this formulation. First, if the 'desired' concentration level is changed, the coefficients of the entire equation must be recomputed. Second, the dual variable information corresponding to this constraint cannot be directly used. Alternatively, since the percentage change in concentration is equal to the difference in percentage changes in total dissolved solids (TDS) and the outflow of water (for small changes, the second order terms are negligible), this constraint can be expressed as a linear inequality in changes in concentration.

The objective function for the linear programming model was the sum of the net returns to agriculture and energy. Maximization of this objective subject to the relevant constraints is the basis for this analysis.

Alternatives for Model Analysis

Using the linear programming model described in the previous section, the following specific alternatives were considered. Alternative I examines the effect of energy development on changes in salinity level at Lees Ferry in 1985 with no control measures. This was accomplished by solving the LP model without imposing the salinity constraint in the model. The solution would result in efficient intersectoral allocation of water resources in the sense that water is allocated to yield equal values of marginal product in all uses. With free transfer of water rights, the market system can be expected to bring about the same results; therefore, the activity level of the salinity constraint will indicate changes in salt concentration with no salinity control measures.

Alternative II investigates how various salinity concentrations can be achieved only through investments in improving irrigation efficiency. Increasing irrigation efficiency would reduce the return flow for a given diversion and would hence reduce the salt load. Main consideration was given only to installation of sprinkler systems under this alternative. The analysis was accomplished by defining an additional set of agricultural production activities for sprinkler irrigation in the model and by suitably altering the salinity constraint to take into account the reduced salt pickup in this case. The results of this analysis not only indicated the amount of investments required to meet a given salinity level, but also showed in which WRSA the irrigation system improvements should be made. By parametrically varying the right hand side of the salinity constraint, the marginal cost of salinity improvements can be obtained from the optimal dual variables.

Under alternative III, the effectiveness of dilution as a salinity control measure was examined. This alternative provides planners with costs of achieving desired levels of salinity concentration through curtailment of upstream water use by not allocating the entire compact-apportioned waters or reducing present water uses. The desired concentration level was specified for the right hand side of the model described under alternative I. By varying it parametrically, the marginal cost of the dilution alternative was found from the corresponding optimal dual variable.

In alternative IV, both control measures defined under alternatives II and III were used to achieve various levels of salt concentration. This alternative indicates the efficient combination of structural and nonstructural programs to meet a given salinity level. The model solutions were obtained for the 1972 salinity levels for alternatives II, III and IV to assess the impact of the EPA regulations. Assuming that a change in concentration at Lees Ferry leads to the same change in concentration for the Lower Basin, the optimal water quality level can be calculated by equating the marginal cost of salinity control for alternatives II, III and IV with marginal benefits to the lower basin users.

Discussion of Results

When energy and agricultural developments as projected for 1985 were allowed without any salinity control measures, the level of concentration of salt at Lees Ferry was found to increase by 9.64 percent or approximately 50 mg/l above the 1972 level. No water transfers occurred since there was sufficient water to meet both demands. The energy sector used 276,000 acre-ft. and the agricultural sector used 2,427,000 acre-ft. Present and potential irrigated land in the basin totaling 1,367,000 acres were fully utilized. Under alternative II, 30 percent of the irrigated land must be put under sprinkler irrigation in order to maintain the 1972 water quality level (Table 1). Irrigation improvements occurred in WRSA 1,2,4,5 and 7. Sprinkler systems in these areas cost $20.2 million annually (Table 2). The costs included the annualized capital and installation costs and variable operating costs. The marginal cost of enforcing the 1972 level by this alternative was $788,000 per mg/l.

The analysis under alternative III indicates that agricultural water use must be reduced as much as 475,000 acre-ft. to reduce salt loading and provide dilution to meet 1972 quality levels. The reduction in water consumptive use decreased agricultural returns by $17.4 million (Table 1), the cost to upper basin users of improving water quality. Of the 125,301 acreage reduction, 102,125 acres were in WRSA 5 (Table 1). The marginal cost of implementing alternative III was found to be $459,000 per mg/l.

Under alternative IV, water use reduced by 305,000 acre feet as compared to uncontrolled development (alternative I). This reduction was brought about by retiring 67,411 acres of irrigated land as well as changing to less water intensive cropping patterns. Also, under this alternative the acreages under sprinkler irrigation reduced from 404,379 acres to 101,511 acres. The control measures to meet the 1972 salinity levels under this alternative were chosen such that the quality improvement achievable by expending an additional dollar on any technique was equal, resulting in minimum control cost. Farm income was reduced by $10.0 million, and the cost of sprinkler systems was $5.1 million. The total cost was less under alternative IV, compared to alternatives II and III, by $5.2M and $2.4M respectively. Alternative IV is clearly the least-cost policy with the marginal cost of $437,000 per mg/l at the 1972 water quality.

However, the marginal costs of reducing salinity to 1972 levels by these three alternatives were greater than the estimated marginal benefit to the Lower Basin users. Annual downstream damages per mg/l for various levels of salinity have been estimated. The various estimates are $54,690 (EPA, 1971), $229,400 (U.S. Department of the In-

TABLE 1. Irrigated Land Under Alternative Control Policies (Acres)

	Alternative I	Alternative II	Alternative III	Alternative IV	
WRSA	Total Irrigated land	Acreage under sprinkler system	Acreage reduction	Acreage under sprinkler system	Acreage reduction
1	340,185	62,954	0	0	0
2	108,114	37,598	22,376	6,266	0
3	191,970	0	0	0	0
4	128,067	36,797	0	0	0
5	198,170	109,671	102,925	95,245	67,591
6	142,063	0	0	0	0
7	223,992	157,359	0	0	0
8	34,920	0	0	0	0
TOTAL	1,367,481	404,379	125,301	101,511	67,591

TABLE 2. Costs and Benefits of Salinity Control

Costs and benefits	Control techniques Alternative II	Alternative III	Alternative IV
Foregone value of output due to water use reduction	0	$17.4M	$10.0M
Cost of irrigation efficiency improvement	$20.2M	0	$ 5.0M
Total cost of maintaining 1972 water quality	$20.2M	$17.4M	$15.0M
Benefits to Lower Basin Users	$12.7M	$12.7M	$12.7M

terior, 1974), and $253,000 (Valentine, 1974) per mg/1. If the salinity level imposed at Lees Ferry is set using economic criteria so that the marginal cost of improving water quality equals the marginal benefit of improved quality, the salinity should be allowed to increase from the 1972 level by 8.34 percent, 7.95 percent, and 7.56 percent for alternatives II, III and IV, respectively.

In Figure 2, line DD, representing the marginal benefit (Valentine's estimate) to Lower Basin users, passes through the step lines SS, WW and JJ at points A, B and C respectively. The step line SS represents the schedules of marginal cost for alternative II, WW for alternative III, and JJ for alternative IV. From Figure 2, it is clear that alternative IV yields the greatest benefit to the entire

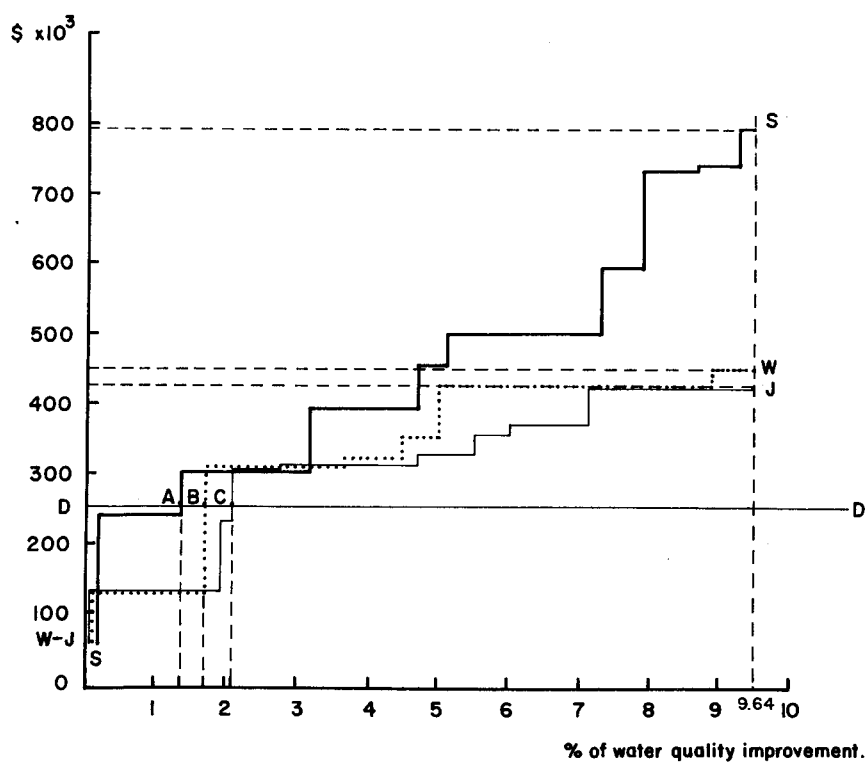

Figure 2. Marginal benefits and costs of salinity control.

basin with an increase of 7.56 percent in salinity concentration from present levels at Lees Ferry. In other words, concentration at Lees Ferry must be reduced by 11 mg/1 from uncontrolled Upper Basin development. The cost of reduced water use is $1.16 million and the cost of irrigation improvements is $0.277 million to the Upper Basin users. Total benefit received by the Lower Basin water users is $2.8 million.

The analysis so far is cast in terms of attaining basin-wide economic efficiency in allocating water resources. Water quality restrictions imposed by the Colorado River System Implementation Plan could be regarded as a means of protecting the water quality of the river for the Lower Basin users. This confers greater benefits to the downstream users sacrificing basin-wide economic efficiency. The equity aspects of the numerical salinity standards are quite clear from Table 2. The total costs to the Upper Basin users (which includes part of federal subsidies) exceed downstream total benefits by $7.5M, and $4.7M and $2.3M for alternatives II, III and IV respectively, annually. The costs exceed the benefits both in total and at margin in all the three cases. At point C in Figure 2, where the costs and benefits are equal at the margin, the downstream damage costs will be $9.9M (avoiding an additional damage of $2.8M from energy development) whereas the cost of reducing salinity by 11 mg/1 will be $1.4M to the Upper Basin.

Summary

If no salinity control measures are taken, future energy development in the Upper Colorado Basin could increase the concentration of salts at Lees Ferry by 50 mg/1. Maintaining the 1972 salinity levels will impose costs on the Upper Basin users that exceed the benefits to Lower Basin both in total and at margin. The minimum efficiency cost of this policy is $3.7M. The efficiency cost of controlling salinity through investments only in sprinkler irrigation system by neglecting the dilution alternative is $8.9M.

This paper has not included several other control alternatives that are proposed in the basin, and therefore, the efficiency costs could be overestimated. Efforts to incorporate control methods such as desalination plants and irrigation canal linings in the model are underway. Further, the optimality criterion used here is only second-best since throughout the analysis, the assumption of zero-discharge by the energy industries and quantitative restrictions on individual state water shares are maintained. Relaxation of this assumption may affect the estimated efficiency costs.

The 1974 EPA regulation does provide for revision of numerical standards every three years. The model in this paper could be potentially used for evaluating efficiency costs and equity implications of alternate policies. The information generated by the model could be used for revising numerical standards over time as growth conditions change in the Colorado River Basin.

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