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Jay C. Andersen
Utah State University

John E. Keith
Utah State University

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STUDIES ON THE ALLOCATION OF WATER OVER SPACE AND AMONG USERS IN AN ARID ENVIRONMENT

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After a decade in a long-term research program at Utah State University it is appropriate to review the concepts, progress and possible changes in direction. In the late 1960's grants were received from the Office of Water Resources and Technology and the U.S. Army Corps of Engineers. Funding was also received from the Utah Center for Water Resources and the Utah Agricultural Experiment Station. These grants enabled a beginning of the research using extensive linear programming models that is still underway, many grants and many people later. The list of publications at the end of this paper form the basis for this report, but are not cited herein. A number of studies in other departments also drew from the program.

To be honest, no thought was given to a decade-long effort at the beginning, although there was hope that funding could be continued beyond the initial three years. Too, full recognition was not made of


2. Professor and Head Department of Economics, Utah State University, Logan, Utah.

3. Assistant Professor of Economics, Utah State University, Logan, Utah.
the research questions which would come up as the model developed and as conditions changed. The research has had the following sequences of questions and findings.

The Supply Model

Faced with a sequence of crucial decisions in an arid state, what are the costs of supplying scarce water to the users in various parts of the state? Particularly, the allocation of Colorado River water and questions of interbasin transfers were important.

The approach taken was to study a number of postulated alternative patterns and levels of demand for water for each of 10 study areas that cover the state. Costs of meeting these demands were minimized using a linear programming model of the economic-hydrologic-physical system. Interbasin transfers and conjunctive use of ground and surface water were used with various operating rules and water-use policies to determine economic effects of some legal, political and social limitations.

It was assumed that for any constant level of Municipal and Industrial water diversions and wetlands use that the remainder of water available could be used for agriculture. The supply map indicating shadow prices for agricultural diversions is shown in Figure 1 for study area 4, which is the Salt Lake City and Orem-Provo areas which is the most heavily populated area in the state. This indicates that a unit of additional agricultural water could be obtained at very modest prices unless the demands for M and I or agricultural uses were very high. With M and I and wetland uses held constant (moving along the abscissa on Figure 1) at the 1965 level of use of 302,500 acre feet produces a more conventional supply curve as found in Figure 2.
Figure 1. Shadow prices of irrigation diversions at alternative levels of both M & I and irrigation diversions.
The shadow prices for M and I diversions at various levels are illustrated in Figure 3. Costs, of course, are higher than for irrigation water, but a number of options are available even maintaining the nearly 800,000 acre foot irrigation diversions that occurred in 1965. A caveat should be made with respect to the potential supply of water. Meeting the quantities on part of these supply maps (the frontier) would result in reduced flow into Great Salt Lake. The palatability and economic feasibility of doing this is still in question at this late date.
Figure 3. Shadow prices of M & I diversions at alternative levels of both M & I and irrigation diversions.
The Agricultural Demand Model

What can agriculture afford to pay for water in each of the 10 study areas? Can agriculture afford the costs of developing and supplying water when it is found and developed locally or if it must be imported?

Demand functions (stepped) were developed for water use in agriculture for each of the ten study areas. These are shadow prices developed by varying the amount of water available. They are shown as Figure 4 to give the general layout of values and shapes. Over time these values have been updated from these that are essentially a decade old, but because the ratios of prices and costs remain relatively stable the values still range from a high of about $10 to $20 per acre foot down to zero. These values are for water use on presently irrigated land. In cases of development of new land the values are somewhat lower because of land development costs. At the present level of water use in agriculture, which is usually at least two-thirds of the way along the stepped functions, these, water values are driven down to generally low amounts. In most cases the price elasticity of demand is relatively elastic.

The Combined Allocation Model

What intrastate water transfers to alleviate water shortages are economically feasible for Utah? If full costs are assessed, are there interbasin transfers that are economically justified for agriculture or for Municipal and Industrial uses?

The demand and supply models were combined in the allocation model for Utah, as shown in a generalized outline of the model in Figure 5. The model maximized net returns or profit, from agricultural use of water given municipal and industrial (M & I), and wetland requirements. By using projected water requirements for municipal and industrial
Figure 4. Demand for water for presently irrigated land.
Figure 5. Diagrammatic representation of the programming model.
users, the changing water allocation for the state could be examined. The efficiency of the timing of the development of alternative sources was also investigated. In particular, the development of the Bonneville Unit of the Central Utah Project was examined. It was clear that the timing of the development was dependent on the growth of M and I requirements, since the value of water in agriculture, a maximum of about $20 per acre foot, was not sufficiently high to warrant importation costs (about $80 per acre foot). Furthermore, various policies which restricted the use of some sources of water caused the timing of the transfer to be hastened. Two specific restrictions were examined: 1) inflows to Great Salt Lake, and 2) groundwater pumping.

As inflows to the Great Salt Lake are reduced, the level of the Lake falls. Since the Lake is very shallow along the shore lines, a significant reduction in inflows leads to the exposure of considerable amounts of Lake bed. Local decision makers generally oppose activity which reduces Lake levels in order to provide for aesthetic and recreational or tourism reasons. Water which could otherwise be utilized in agricultural or M and I uses is required to maintain Lake levels.

In Utah, groundwater pumping is restricted to maintain the present artesian head of the groundwater reservoir. Groundwater in the area 4 Basin is plentiful. About 56,000 additional acre feet of groundwater could be pumped at safe yield, although artesian head would be reduced. Presently, much of the annual recharge which maintains the artesian head eventually flows into the Great Salt Lake.

The limitations on groundwater pumping for varying levels of surface water inflows were examined to determine the resulting timing of the development of the Bonneville Unit of the Central Utah Project. In
Figures 6 and 7, these effects can be seen. If pumping is allowed, development of the high cost imported water can be postponed until near the year 2000 while maintaining the present Lake levels. For reduced Lake levels, even further postponement may occur. These institutional restrictions cause M and I users to pay a higher price for water than would have been the case if no restrictions were imposed.

The programming model results were used to calculate the additional cost water users bear as a result of the institutional restrictions. Supply curves were generated for the Wasatch Front in which inflows to the Great Salt Lake were greater than or equal to 850,000 acre feet annually, so that some water level reduction was allowed. For levels of requirements from 1965 to 2020, the allocation was examined to determine the additions to cost which users would have to pay, as in Figure 8. The difference between the supply curve $S^4$ and $S^4'$ is the loss to users which results from the higher supply curve over the time horizon. These values, which we have called a loss in producer's surplus, are quite significant. Examination of institutional constraints on allocations and the costs which result should facilitate better decision making.

The Water for Energy Model

Must agriculture be sacrificed for energy development? With agricultural use as the marginal user of water, is the agricultural industry apt to lose its viability by having water bid away to energy production plants and the accompanying municipal development?

At present many of the Western States are faced with, and in some cases, delaying critical decisions on energy development because of lack of an information base. In general, Utah and other Western States have promulgated the idea that available water is critically scarce. This
Figure 6. Bonneville Unit diversions with alternative inflows to Great Salt Lake (no pumping).

Figure 7. Bonneville Unit cup diversions with alternative inflows to Great Salt Lake (with pumping).
Figure 8. Losses in producers' surplus in HSU 4. (Study area 4)*

*The symbols used in Figure 8 are defined as:

- $MC_{\text{TRANS}} = \text{Marginal Cost of Transferred Water}$
- $Q_{\text{LRECH}}^4 = \text{Quantity of Low-Cost Recharged Water to Replace New Groundwater}$
- $MC_{\text{LRECH}}^4 = \text{Marginal Cost of Low-Cost Recharge in HSU 4}$
- $Q_{\text{HRECH}}^4 = \text{Quantity of High-Cost Recharge to Replace Low-Cost Recharge}$
- $MC_{\text{NRECH}}^4 = \text{Marginal Cost of High-Cost Recharge in HSU 4}$
- $Q_{\text{TRANS}}^4 = \text{Quantity of Water Transferred to Replace High-Cost Recharge}$
- $MC_{\text{GW}} = \text{Marginal Cost of Groundwater in HSU 4}$
- $Q_{\text{GW}}^4 = \text{Quantity of Groundwater Used in HSU 4 on M&I Requirements}$
leads to great concern and a propensity to invest heavily in using all that we are "entitled" to use. We examined the effects on water allocations in both agricultural and energy sectors given various alternatives for allocation and development.

The previous models were modified by adding energy sectors in much the same format as the agricultural demand model discussed previously. The results from the modeling indicate that there is sufficient water in Utah's allocation of the Colorado River to provide for medium levels of expected energy development, including moderate levels of oil shale, with only minimal loss in irrigated agriculture. In addition, most of the reduction in irrigated acreage would optimally be in the less productive Class IV and pasture lands, or in the reduced development of potential new irrigation projects indicated in the model results. Only during severe prolonged drought would these moderate energy developments constrain current prime irrigation (Class I through III lands presently irrigated). Substantial temporary reduction in these acreages would likely occur with even minimal energy production under those circumstances.

On the other hand, high levels of energy development could take place only at the expense of almost all irrigation in the Colorado River Basin in Utah. Large scale oil shale and tar sands operations will require reallocation of most of the water currently used in agriculture in several of the 10 study areas. Liquefaction, gasification, and electrical generation at high levels would also be expected to retire some cropland from irrigation by taking water from the relatively low-valued agriculture use. However, a high percentage of the retired land may be used for dryland crops. Furthermore, the large-scale development of most of the energy resources in the Colorado River Basin
might be expected to substantially reduce water available for transfer to agricultural users in the western part of the state. Given the high shadow price of water for the various energy sectors, and the relatively low shadow price for current marginal agricultural production, the use of water in energy is economically sensible. Retention of water in agricultural pursuits at the expense of energy production is inefficient. Even the municipal users along the Wasatch Front would not have a sufficiently high demand to bid significant amounts of water from the Colorado River Basin energy producers, assuming the current estimates of M and I demand curves for water. For the near future, the quantity of water appears not to be the constraining factor on energy or agricultural production.

Other factors may be important. Air and water quality standards may be of great importance, as they affect the profitability of energy production. Also, the social desirability of severely reducing irrigation along the Upper Colorado River in order to produce relatively expensive energy, compared to energy costs in other regions, may be doubtful.

The pattern of potential water right transfers from agriculture to energy sectors has interesting implications. Allowing transfers of diversion rights rather than consumptive use rights would cause negative externalities to downstream users, since energy processing can be expected to consume a larger proportion of diversions. In fact, indications are that energy developments will exercise "total containment" of water to avoid effluent problems. Thus, current irrigation return flows might not become available to downstream users. Utah law and practice seems not entirely clear on this point. Several decisions indicate that downstream flows must be maintained, but the record lacks consistency. The research points up the need for consistent, efficient, and equitable institutions on this matter.
Water Quality Modeling

Are water quality restraints restrictive on agriculture or energy? Would the changes in use or increases in use reduce flows or load the streams with additional salts which would violate non-degradation standards?

The Department of Energy projection of probable energy production levels for the year 2000 in the Colorado Basin in Utah would result in an increase of about 25,000 acre feet of consumptive use, which is less than a 1 percent decrease in water flow. The development of the projected level of energy production in all the Upper Basin states, coupled with an additional 230,000 irrigated acres, would result in less than a 10 percent increase in salinity concentration at Imperial Dam. Full scale energy development in Utah alone would reduce outflows and increase salinity by about 3 to 5 percent. The imposition of non-degradation standards have significant allocative effects in the Upper Colorado Basin, according to the model results. A strict nondegradation standard would prevent further development of the 300,000 to 600,000 acre feet of Utah's unutilized portion of the Upper Basin share of water which currently provides dilution of natural and agriculturally-related salt loading.

If water quality standards do in fact limit consumptive use to present levels, there may be an increase in water quality as energy resources are developed. Water use will not increase (assuming water rights downstream are protected), but salt loading from existing agriculture will be reduced. Depending upon the area in which irrigated agriculture is retired, loading may be reduced. Selective retirement through state approval of water right transfers may be a significant tool by which stream standards are met, energy developed, and impact on irrigated agricultural in the Colorado Basin mitigated. Selected retirement of
agricultural areas which produce most salts by transfers of water rights within that area to energy development may allow both energy development and some increase in irrigated acreage.

Irrigation practices and salinity control measures which would reduce salt loading from return flows and thereby allow the use of at least a portion of currently unallocated water are under consideration. The primary practices are 1) conversion of some traditional irrigation systems to sprinkling, 2) canal lining, and 3) construction of evaporation ponds and desalting plants. Results from the models indicate that each of these practices will be undertaken to some degree while maintaining a positive, but reduced, profit in agriculture. In several cases there is need for a subsidy, if maintenance of irrigated acreage is a policy objective, since long term profitability is very low relative to the costs of borrowing and the opportunity costs for alternative investment.

The economics of three alternative water quality control practices were examined for the Upper Colorado River Basin--increased agricultural efficiency through sprinkling and canal lining, treatment of salt discharges, and a combination of those practices--assuming the Department of Energy projections and new irrigation were in place. The cost of reduction of salinity includes the annualized investment, operation and maintenance, and foregone income (where appropriate) for each alternative treatment. By comparing these costs with downstream benefits, some measure of economic efficiency with respect to salinity control can be estimated. Benefits to reduced salinity in the Lower Colorado Basin in the form of reduced damages to agricultural production and municipal and industrial users have been estimated by several researchers. An estimate of $253,000 in damages per miligram per liter is the most widely used. This is
shown as DD on Figure 9. It appears that maintenance of current instream quality is economically inefficient, but that the increase in salinity of nearly 10 percent, which would occur in absence of these practices, can be efficiently reduced to the level of about 2 to 4 percent, depending on the practice (points A, B, and C on Figure 9). A question remains, however. Some sprinkler irrigation is economically feasible from the individual farmers perspective irrespective of the salinity problem. Canal lining, land retirement and other sprinkler applications are not. The burden of the cost of treatment could be borne by upstream users, if treatments were mandated; by downstream users in the form of additional water costs which could be used to subsidize developments; or by the general treasury fund. The distribution of the costs would be a political decision.

Thus, there exists mitigating treatment practices such as sprinkling, canal lining, and selective retirement which will allow energy and irrigation development and conformity with non-degradation standards. Some of these may be economically feasible irrespective of water quality considerations. Others must be mandated or subsidized. Non-degradation standards may be economically inefficient in that the incremental benefits from maintaining or reducing salinity are less than marginal treatment costs imposed on upstream users.

The total containment policy in energy development may be counterproductive in some cases. If high quality water is removed from the stream rather than returned at a somewhat lowered quality, but which is still better than the ultimate downstream water, the net effect could be a degradation in water quality. This depends of course on the alternate use of the water which would have a lessened diversion requirement for
Figure 9: Marginal Cost and Marginal Benefit of Salinity Control in 1985.
S: Sprinkling and Canal Lining
W: Water Treatment
J: Combination
energy. The possible lowering in quality could result from pickup associated with the alternate use and a lessening of available dilution water.

**Air Quality Modeling**

Do air quality restrictions affect the level and distribution of water transfers? What are the relationships between air and water quality constraints?

Air quality constraints reduced the electrical generating capability and other energy resource processing capability rather substantially for several study areas. Thus, the air quality limits to production in many cases reduce or eliminate the competition between agriculture and energy for water. We can, therefore, say that air quality constraints currently appear to be more restrictive on energy development in Utah than water quality or quantity constraints.

**Summary and Conclusions**

The results from the rather extensive modeling work done at Utah State University indicate that some popular conceptions of problems associated with energy developments and agricultural maintenance and development may be mistaken. Water scarcity is less of a problem than sometimes represented, except for certain parts of the state in the Great Basin. Air and water quality constraints seem to be far more important. These air quality constraints as they are currently interpreted are the main limiting factors for energy development in Utah. Whether the clean air benefits as presently interpreted exceed the foregone returns to energy production is an interesting question that needs additional evaluation.
The type of modeling used in these studies has been useful in generating information which is useful for policy-making. An interesting challenge is to further build trust of governmental officials to utilize these data. Our own efforts always need to be tempered by realizing that the real world situation and decision variables are not perfectly modeled. We must be cautious in our pronouncements. Constant updating is needed to build in appropriate institutional limitations.

Finally, the exercise of model building using a structured approach allows researchers from several disciplines to effectively coordinate efforts. Government officials, too, can and have contributed valuable inputs to make the models more useful. The process of communication and cooperation has been a useful result of these studies.
Literature


