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### Authors

Vaux, Henry James, Jr.  
Marsh, Albert W

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ECONOMIC POTENTIALS FOR AGRICULTURAL WATER-SAVING  
USING ALTERNATIVE IRRIGATION TECHNIQUES

by

*Henry James*  
H. J. VAUX, JR., and ALBERT W. MARSH  
Department of Soil and Environmental Sciences  
University of California, Riverside

Office of the Director  
CALIFORNIA WATER RESOURCES CENTER  
University of California                      Davis, California 95616

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## ABSTRACT

More efficient use of water by irrigated agriculture in California will likely be necessary if the significant economic role played by this industry is to be maintained in the future. Necessary economic data and methodologies are developed to assess the extent to which water savings can be realized through widespread adoption of water-saving irrigation technologies. Special emphasis is placed on identifying the extent to which water-saving irrigation technologies substitute energy for water. An assessment of the methods developed was performed on the agricultural sector of western Riverside County of southern California.

A linear program model develops the responses of agricultural production to changes in the cost and availability of irrigation water and pumping energy. A new method for limiting cropping pattern shifts is analyzed. The results of the model and the possible impact of the model's assumptions on these results are discussed.

Some conclusions drawn from the analysis include: an increasing rate of decline in irrigated acreage, particularly of field crops, due to increasing resource prices; a much higher elasticity of demand for imported water than for groundwater; increasing use of sprinkler and particularly drip irrigation as water price rises; and a large potential for water stressing of crops if better information becomes available on water production functions. Implications of the results are discussed and ways of improving the accuracy of the model are suggested.

## INTRODUCTION

The increasing financial and environmental costs of developing new water supplies suggest that California may soon be faced with a situation in which the supply of water may be regarded as essentially fixed. California agriculture makes use of approximately 85% of the state's water supply. If the significant role that California agriculture plays within the State and the nation is to be maintained, it may be necessary to identify means that stretch and make more efficient use of water supplies devoted to agriculture. This project focused on the development of economic data and methodologies necessary to assess the extent to which water savings can be realized through the widespread adoption of water-saving irrigation technologies. Special emphasis was also placed on identifying the extent to which water saving irrigation technologies substitute energy for water.

The objectives of this project included both the development of data necessary to identify the economic potentials of water saving irrigation technologies and the development of appropriate methodologies to be used in analyzing the data. More specifically, the project involved:

1. Identification of the constraints that may impede shifts from surface irrigation technologies to drip and sprinkler technologies.
2. An assessment of the cost of alternative irrigation technologies. Special attention was devoted to specifying the energy costs of operating different irrigation systems.
3. An assessment of the energy required to manufacture, transport and install alternative irrigation technologies. This assessment focused on the energy "embodied" or "sequestered" in alternative technologies.

4. A comprehensive assessment of the extent to which substitution possibilities in irrigation could be realized. This assessment was confined to the agricultural sector of western Riverside County of southern California.

In the following report the pertinent data and methods are reviewed and the results are presented and discussed.

#### DATA AND METHODS

At the outset, it was envisioned that this project could be completed with secondary data available from agency and published sources. This proved to be true with one exception. Although there are a number of sources of data on the energy required to manufacture, transport and install irrigation systems, there is a very wide disparity between the actual figures (see Batty, et al., 1975). A careful review of the literature suggested that the estimates of embodied energy in materials used in manufacturing irrigation equipment had been developed with inconsistent and sometimes unspecified methodologies. As a result, it became necessary to alter the focus of the project somewhat to place more emphasis on the development of accurate estimates of the energy embodied in alternative irrigation technologies. The project thus focused on two separate but interrelated sets of questions: 1) What is the most appropriate means for measuring energy embodied or sequestered in irrigation technologies and what are the magnitudes of that energy?; and, 2) Under what conditions will irrigation technology shift in response to increasing relative prices of energy and water and what is the nature of the shift? Since the substance of the answers to these questions differs quite materially, each set of questions will be addressed separately.

### Embodied Energy

The notion of embodied energy or fixed energy has been developed and advanced predominantly by non-economists. The notion is premised, in part, on the belief that acute energy scarcities threaten the bases of industrialized economies. To forestall that threat, the argument holds that the energy consumption implications of resource development alternatives should be given far more careful consideration than has historically been the case. In the extreme, it is argued that the most desirable alternative will usually be the one entailing the smallest commitment of energy (Odum, 1973). This argument was the prime motivator behind the development of techniques of net energy analysis which serve to delineate the total energy commitment entailed by both technological and institutional responses to resource scarcity.

The major conceptual problem with net energy analysis is that it entails an energy theory of value, similar in many respects to earlier theories that ascribed all value to land or to labor. Net energy analysis, then, may be inappropriate or misleading due to the underlying presumption that energy is ultimately the only true scarce resource. On this ground alone, it is argued that net energy analysis should be rejected and that alternative investments and technologies be evaluated via the more traditional and conceptually sounder modes of economic analysis (Huettnner, 1976). This argument, while valid as far as it goes, ignores the fact that net energy analysis may be useful when combined with economic analysis. There are at least two reasons why this is true. First, it is well established that many if not all energy markets are imperfect markets subject to a wide variety of price distorting features. It follows, then, that the price of energy is not always a valid representation of its relative scarcity value. As a consequence, analyses

that accept prices as adequate measures of value may yield distorted conclusions about the desirability of opting for energy intensive technologies.

A second reason for believing that net energy analysis has useful, if limited, attributes revolves around the likely future behavior of energy prices. For a variety of reasons, energy in the United States, has historically been priced at artificially low levels. One policy response to conditions of sharply tightening supplies has been to remove, albeit progressively, many of these artificial constraints. This means that both the increasing relative scarcity of energy and the relaxation of price constraints are driving relative energy prices to sharply higher levels. In the face of increasing relative energy prices, there will be an inevitable tendency to substitute inputs with relatively stable prices for increasingly expensive energy inputs. The result is that energy intensive irrigation technologies that hold promise for reducing water used in agriculture may not be voluntarily adopted by growers. Moreover, there is the associated danger that public policies which attempt to induce growers to adopt such technology may simply promote inefficient substitution of energy for water. As a result, it is important to know what magnitudes of energy are involved in the manufacture, transport, installation and operation of alternative irrigation technologies. It is in this context that net energy analysis was employed in assessing the economic potentials of alternative irrigation technologies.

Net energy analysis is commonly accomplished utilizing one of three different methods: a modification of the familiar economic input-output analysis; process analysis; or bio-energetic analysis. Bio-energetic analysis, which accounts for energy losses occasioned by disruption of natural systems in addition to more conventional forms of energy consumption,

was rejected as a possible mode of analysis both because it has not been fully developed from a conceptual standpoint and because the data requirements were far too demanding for a project of this nature. A review of the literature on process analysis and the modified input-output analysis suggested that neither method was clearly preferable. Briefly, process analysis involves the identification of direct energy inputs associated with the production of some product. Indirect inputs are measured by identifying backward linkages in the production processes and estimated the energy embodied in the backward linked inputs. Backward linkages are identified for some arbitrary number of stages leading up to the manufacture of the product in question. The number of linkages to be considered is usually determined using judgement as to how far back it is necessary to take the analysis to capture the preponderance of energy embodied in the final product. As a result, process analysis, while straightforward to apply to specialized industries or products, abstracts from some of the indirect relationships in an economy and thus neglects to measure some quantity of indirectly embodied energy. This quantity is essentially unknowable and, as a result, process analysis yields results that virtually always underestimate the actual amounts of embodied energy.

Input-output analysis, on the other hand, involves a seemingly straightforward modification of the economic method first put forth by Leontief for measuring all direct and indirect contributions to final product in an economy. Simply, the conventional economic formulation can be depicted as follows:

$$1) \quad X = [I - A]^{-1} y$$

where

$y$  = a vector of final demands

$X$  = a vector of total outputs



A = a matrix of technical coefficients or  
direct effects.

To modify this analysis it is only necessary to reformulate the input-output framework so substitute Btus for dollars in the appropriate transaction. All transactions between primary energy producing (including electricity) sectors are formulated in terms of Btu/Btu, transactions between energy sectors and non-energy sectors are specified in terms of either \$/Btu or Btu/\$, depending on the nature of the transaction, and all transactions between non-energy sectors remain in \$/\$. It is then a simple matter to compute the total embodied energy in any product. The principal strength of this analysis is that it captures the totality of both direct and indirect effects. The principal weaknesses are that available data bases in the form of A matrices are usually somewhat out of date and the data is often highly aggregated.

Inasmuch as both methods have strengths and weaknesses, it was decided to utilize both to analyze the energy embodied in irrigation equipment in an effort to determine both the feasibility of utilization and the accuracy of each.

Process analysis was applied to aluminum, steel and PVC. Schematics tracing the basic steps of manufacture for bauxite and iron ore were prepared and used as the framework for developing detailed estimates of energy inputs. Data on actual energy inputs were obtained from aluminum companies in the Pacific Northwest and from steel companies in the Pacific and Midwestern regions. Data for the manufacture of PVC was obtained from the Johns-Manville Corporation, a large manufacturer of synthetic chemicals.

The input-output analysis was first done with an 80 sector I-0 table developed by the Department of Commerce. The level of aggregation inherent in this table proved to be too great to make it useful for an activity as specific as the manufacture of irrigation equipment and further efforts were made with a 412 sector table in which aluminum, steel and synthetic chemical production activities were reported in more detail. Ultimately, the two methods were evaluated on the basis of data requirements, accuracy of available data and a comparison of the estimates.

### Analysis of Irrigation Technologies

The analysis of irrigation technology was broadly conceived in an effort to: 1) assess the impact on energy and water inputs of adoption of new technologies, and 2) assess the relative importance of technology switching among a number of potential responses that could be selected by growers in a region faced with increasingly scarce energy and water. Mathematical programming techniques were initially identified as the most promising because of their capacity for handling the large number of variables and constraints necessary in characterizing the agricultural industry of a region. Additionally, such models can be structured so as to account for the input implications of alternative technologies as well as to assess the relative attractiveness of technology switching among an array of potential responses to resource scarcity.

An initial analysis identified a number of possible grower responses to increasing relative prices of water and energy. Five modes of response or adaptation were identified as follows:

1. A shift in cropping patterns to favor less water intensive crops.
2. Adoption of water-saving irrigation technology.

3. Reductions in applied water resulting in moisture stress in the crop and an associated yield reduction.
4. A shift in the source of water supply from surface water to ground-water or vice versa.
5. Removal of irrigated land from production.

The problem, then, was to develop a model of a regional sized agricultural sector that could adapt to water shortages in any of these ways. A modified linear programming model was developed, predominantly because of the difficulties associated with obtaining the accurate crop price information required by quadratic programming approaches. The model is reproduced on the following page.

The uniqueness of the model lies with the introduction of flexibility constraints which serve to restrict crop shifts to some function of initial conditions and to prevent unrealistic solutions in which all acreage is shifted to a single crop. Additionally, this form of constraint introduces an element of risk aversion into the model by restraining widespread shifts to crops with which growers may be unfamiliar.

The area selected for analysis was western Riverside County. Although this area is not especially important to the total agriculture picture in California nor is it likely to become so, it contains a richer mix of crops and irrigation systems than most other agricultural regions. Additionally, the region is relatively homogeneous in terms of climate and soil variability and locational advantages of individual growers are probably non-existent. Moreover, this region may be especially susceptible to energy and water supply curtailments and price increases.

LINEAR PROGRAMMING MODEL

$$1) \text{ Max Net Revenue} = \sum_a \sum_b \sum_c \sum_d [E(P_a) \cdot E(Q_{ac}) - P_d - W_{abc} - VC_{abcd} - FC_{abd}] \cdot X_{abcd}$$

Subject to:

$$2) \sum_a \sum_b \sum_c W_{abc} \cdot X_{abc, 1} \leq \text{GW (groundwater constraint)}$$

$$3) \sum_a \sum_b \sum_c W_{abc} \cdot X_{abc, 2} \leq \text{SW (surface water constraint)}$$

$$4) \sum_a \sum_b \sum_c \sum_d E_{abcd} \cdot X_{abcd} \leq \text{TE (energy constraint)}$$

$$5) \sum_a \sum_b \sum_c \sum_d X_{abcd} \leq \text{TA (acreage constraint)}$$

$$6) \left. \begin{array}{l} A_a^L \leq \sum_b \sum_c \sum_d X_{1,bcd} \leq A_a^U \\ \vdots \\ \vdots \\ A_a^L \leq \sum_b \sum_c \sum_d X_{abcd} \leq A_a^U \end{array} \right\} \begin{array}{l} \text{Flexibility} \\ \text{constraints} \\ \text{for each} \\ \text{a crops} \end{array}$$

Where:

GW = amount of groundwater available in acre feet

SW = amount of surface water available in acre feet

TE = amount of energy available in KWH

TA = maximum allowable total acreage

$A_a^L$  = lower acreage bound for crop a

$A_a^U$  = upper acreage bound for crop a

$X_{abcd}$  = acres of crop a, irrigation system b, water application level c, and water source d

$E(Q_{ac})$  = Expected value of crop yield in units/acre/year

$E(P_a)$  = Expected value of crop price in \$/unit

$W_{ab}$  = water use in acre feet/acre/year

$P_d$  = water cost in \$/acre foot

$VC_{abcd}$  = other crop production costs which vary with applied water level, in \$/acre/year

$FC_{abd}$  = other production costs which do not vary with applied water level, in \$/acre/year

A detailed discussion of the data required for model and the source from which it was ultimately obtained can be found in Hatchett (1980). A brief summary follows:

1. Twelve major crops and crop groups were identified for the area including 4 perennial crops, 5 field crops, and 3 vegetable crops. They accounted for 95% of the irrigated acreage in the region in 1977. Information on crop acreages and average revenue per acre were obtained from the Riverside County Agricultural Commissioner. 1977 acreages and six-year averages for crop revenues were used.
2. Annual cultural costs per acre for each crop were obtained from a variety of sources. These costs were exclusive of costs associated with water supply or irrigation.
3. Seasonal water use figures for each activity were ultimately computed utilizing the Penman method (see Doorenbos and Kassam, 1979). Published data were not used because they did not reflect differences associated with the use of flood, furrow, handmove sprinkler, or drip irrigation systems, the four systems selected for analysis.
4. The pumping energy required for each activity included both energy to convey water to the farm, either through surface distribution systems or from the groundwater, and the energy necessary to operate the different irrigation technologies. Some pumping energy estimates were obtained from the literature while others were developed for situations unique to western Riverside County.
5. Information on application efficiencies of irrigation systems was found to be scanty and unreliable. The application efficiencies usually assumed to exist by other researchers were ultimately used. (It should be noted that one of the findings of this study was that application

efficiencies cited in the literature are apparently little better than educated guesses. This finding was subsequently used to obtain funding from the U. S. Department of Agriculture to conduct a more thorough study of both field application efficiencies and the implications of revising the definition of application efficiency to make it consistent with notions of economic efficiency).

6. Irrigation system costs were obtained both from the published literature and through correspondence with irrigation consultants.
7. Water prices were obtained from the Western and Eastern Municipal Water Districts of Riverside County. The retail prices charged by these districts were assumed to be reflective of prices charged by the smaller water districts in the regions. Energy prices were derived from the rate schedules of Southern California Edison Company. Information made available by the Edison Company was used to weight the price by pump size and derived a weighted average price for the region.
8. The development of ground and surface water constraints proved to be more difficult than originally envisioned. Ultimately this information had to be inferred from a variety of sources.
9. The energy availability constraints were arbitrarily chosen at a non-restraining level and subsequently reduced in step-wise fashion in the analysis since no reasonable estimate on the limit of power available for groundwater pumping was available.
10. A single water yield production function for corn was selected for use with all crops. This was done because little is known about reductions in crop yield when moisture is limiting. The corn function was estimated in a climatic regime similar to that prevailing in western Riverside County and had intuitive appeal because its quadratic form exhibited decreasing marginal productivity of water.

11. The flexibility constraints were estimated through a procedure in which the average percent change in acreage for each crop class over several years was regressed against a weighted average of maximum net revenues for the crop class over the same period of time.

## RESULTS

### Embodied Energy

The comparative results of the input-output analysis for aluminum, steel and PVC inputs to irrigation equipment are summarized in Table 1 below.

TABLE 1  
Embodied Manufacturing Energy for Aluminum, Steel, and  
PVC Components of Irrigation Equipment  
(in Btu's per pound)

	I - O Analysis	Process Analysis
Aluminum	$10.75 \times 10^4$	$11.23 \times 10^4$
Steel	$18.54 \times 10^4$	$19.15 \times 10^3$
PVC	$43.46 \times 10^3$	$46.43 \times 10^3$

While the results are within 10% of each other it is significant that the results of the I-0 analysis are lower than those of the process analysis in each instance. This is contrary to expectation. One of the strengths of I-0 analysis is its capacity to account for all direct and indirect energy inputs. This is in contrast to process analysis where indirect inputs that are assumed to be minor are ignored while attention is focused on accurate estimation of the major direct and indirect energy inputs. If the data used

in each of the analytical procedures are of comparable quality, it will always be true that I-O analysis yields higher and (presumably) more accurate results. In this instance, the expected results were not obtained.

This apparently anomalous result appears to be attributable both to significant qualitative differences in the data used in the two analyses and to at least three significant methodological problems with the I-O analysis. The data utilized in the process analysis was reflective of conditions faced by the pertinent industries in 1978-79. Moreover, the information was available in a highly disaggregated form. In fact the information was so disaggregated that it permitted an analysis of energy differences on a firm-by-firm basis.

This contrasts with the data utilized for the input-output analysis which was reflective of conditions in 1968. Although implicit deflators were used to place both data sets on the same time footing, disparities still remained. The 1968 data base characterizes an economy in which energy was cheap and plentiful. As a consequence, the data does not capture the inevitable reactions of the economy to tightening energy supplies and increasing energy prices that began to occur in 1973. This fact alone would suggest that I-O analysis would lead to an overestimate of current energy intensity and provide additional support for the supposition that I-O estimates of embodied energy should be systematically higher than those obtained with process analysis.

The failure to observe the expected relationship between I-O and process analysis results is apparently attributable to the level of aggregation of I-O data and to problems attendant to the allocation of capital and the treatment of imports in I-O analysis. Aggregation problems arise, for example, because even in the 420 sector I-O model primary aluminum refining is broken



only into three sub-sectors. It is not at all clear that the energy intensity of any of these sectors is characteristic of the aluminum rolling and extruding. Similar problems exist for steel and PVC.

A further distortion of unknown magnitude is introduced by the essentially arbitrary fashion in which capital is allocated among industries. This problem is discussed at some length by Kirkpatrick (1974). There seems little question but what judgemental methods of allocation result in distortions and yet a conceptually acceptable means of allocation is not at hand. Similar distortions are introduced in resolving the problems of treating imports. These distortions are especially significant where imported energy is involved and clearly pervades the entire analysis (Bullard and Herendeen, 1975).

Input-output analysis, then, shows little promise for the estimation of energy embodied in irrigation equipment. It has the potential to be useful in those rare instances where virtually all production stages for irrigation equipment are located in the same region where the equipment is ultimately used. Even in this instance, however, problems of handling capital allocation and imports may introduce significant distortions. Accordingly, the principle conclusion of this phase of the project is that process analysis is the most accurate and appropriate way to estimate energy embodied in irrigation equipment.

The results of this work have been used, in part, to reformulate a computerized routine for calculating embodied energy originally devised by Wensink, et al., 1976. In cooperation with investigators at Oregon State University, the routine was first adjusted to correct a number of computational and substantive errors. Subsequently, the calculations of embodied energy have replaced previous estimates which were highly arbitrary. Finally, the routine has been changed from a batch to an interactive mode. This latter

change greatly simplifies the task of computing embodied energy for a wide variety of irrigation systems and design variations. A user manual for the improved program is currently in preparation.

#### Analyses of Irrigation Technologies

The analysis of the impacts of increasing water and energy scarcity was conducted by developing 20 scenarios representing combinations of variations in the cost of surface water, the cost of energy, groundwater availability, surface water availability, and energy availability. The data included in each scenario are presented in Table 2. The results of the analyses of these scenarios are summarized in the following paragraphs. The details of the analyses can be found in Hatchett (1980).

The removal of acreage from production in the region is the likely first response of growers to increased costs. The decline appears limited to about 20% of the total land area even if water costs are trebled (to \$300/A.V.) and energy costs rise by a factor of 10 (to \$0.20/KWH). The decline itself is more pronounced with water cost increases than with energy cost increases. The reason for this is that surface waters are sensitive predominantly to water costs while groundwater is sensitive to energy costs. Inasmuch as groundwater users can switch to surface water more readily than surface water users can change to groundwater, this conclusion is not surprising. An important qualification, however, stems from the fact that changes in total acreage are critically dependent upon the parameters used in the flexibility constraints. This underscores the need for care and accuracy in estimating the flexibility constraints and suggests the desirability of accounting more directly for physical and agronomic factors when specifying the constraints.

TABLE 2  
SCENARIOS OF RESOURCE PRICES AND AVAILABILITIES

Cost of surface water in \$/A.F.	Cost of energy in \$/KWH	Groundwater available in 1000's of A.F.	Surface Water available in 1000's of A.F.	Energy Available in millions of KWH
100	.0274	200	50	200
150	"	"	"	"
200	"	"	"	"
300	"	"	"	"
100	.05	"	"	"
150	"	"	"	"
200	"	"	"	"
300	"	"	"	"
100	.10	"	"	"
150	"	"	"	"
200	"	"	"	"
300	"	"	"	"
100	.20	"	"	"
150	"	"	"	"
200	"	"	"	"
300	"	"	"	"
100	.0274	175	50	200
100	.0274	150	50	200
100	.0274	200	40	200
100	.0274	200	30	200
100	.0274	200	50	150
100	.0274	200	50	125

A shifting of crop mix is the second most likely response. Orchard and vegetable crops are virtually non-responsive to increasing water costs while acreage devoted to field crops declines rapidly in the face of increased water costs. Since, field crops are, in almost every case, less profitable than orchard and vegetable crops and are more intensive users of water, the conclusion is logical. All crops show a slight decrease in acreage in response to increases in energy prices. The conclusion that changes in crop mix appear to be solely a function of water costs is also critically influenced by the form of the flexibility constraints and must be interpreted carefully.

A shift in resource use may often precede changes in acreage and crop mix, but only where such shifts are possible. The analysis for western Riverside County shows that as energy costs rise, surface water will be substituted for groundwater. This conclusion is somewhat misleading, however. Energy cost increases are felt at the farm level through increased groundwater pumping costs and have virtually no short-run impact on surface water cost. In southern California virtually all surface water is imported and the energy costs of conveyance are established by long-term contract. Thus, increases in energy costs are only manifested in surface water costs at lagged time intervals when the long-term power contracts are renegotiated. It can be expected that when surface energy costs increase, they will increase quite sharply and induce some shift from surface water to groundwater where contractual and repayment arrangements are flexible enough to permit it.

The shifting of irrigation technologies is a third or fourth level response from a regional standpoint, although it is clearly an important response. As water costs increase, through a range of \$100 to \$200 per acre

foot, an overall shift from surface to pressurized systems occurs. This shift represents both a substitution of on-farm energy for water and a substitution of capital for water. If the price of water is increased from \$200 - \$300 there is a shift away from pressurized to surface systems attributable to an easing of the groundwater constraint due to acreage reduction.

In the face of substantial increases in energy costs and no change in water costs, pressurized systems are replaced by surface systems as water is substituted for energy. This conclusion is again dependent upon the situation in western Riverside County (and indeed in most of southern California) where increases in energy cost are reflected in the price of imported surface water only with a substantial time lag. These results support a general conclusion that for cropland irrigated with imported water, overall energy and water use are complimentary even though they tend to be substitutes at the farm level. Thus in regions that rely substantially on imported water, an improvement in water application efficiency also reduces energy use.

Finally, the analysis suggests that moisture stressing may not be an especially likely response to increasing water and energy costs. This conclusion is tempered, however, by an almost total lack of information on the nature of crop production functions. The analysis shows that if production functions do indeed exhibit declining marginal productivity, the potential for moisture stressing may be large. However, in western Riverside County, lower profits resulting from moisture stressing are unlikely to be accepted by growers because of the relatively high opportunity cost of land. Moisture stressing could prove important in other regions where land development pressures are not as acute, however.

Finally, two general qualifications on the above conclusions should be noted. The agricultural industry in western Riverside County, while rich in crop mix and irrigation technologies, is not representative generally of California agriculture. In particular, the fact that growers can escape increasing energy costs in the immediate short-run by utilizing surface water means that their responses to increasing energy costs may not be typical of California growers generally. Additionally, the fact that such growers may regard the energy costs needed to pressurize surface water supplies as sunk or fixed means that they may switch from surface to drip or sprinkler technologies more readily than their counterparts who must consider the energy cost of system pressurization as a variable cost.

The linear programming format as modified by the flexibility constraints also introduces distortions. While the program formulated for this study represents an improvement over most of those previously developed to analyze analogous issues, problems still remain to be resolved. The linearity of supply response functions is particularly troublesome. The flexibility constraints have also introduced distortions which may be attributable to the relatively crude fashion in which they were estimated. Future work includes attention to the development of more sensitive and sophisticated ways of specifying the flexibility constraints. Withal, the required linear programming model serves well in the analysis of contextual or regional variables that may crucially influence the extent to which water and energy are substitutable.

## CONCLUSIONS

This project has served as a beginning for far more extensive research involving the energy and water use attributes of alternative irrigation systems and their role in California agriculture. Largely as a result of work completed in this project, funding has been secured to undertake a larger and more sophisticated project of a similar nature in the Central Valley of California. This project, which is supported by grants from the California Department of Water Resources and the U. S. Department of Agriculture, will be accomplished over a three-year period.

Several issues that were raised but not resolved during the course of research reported here are being directly addressed in the follow-up project.

1. Methods for estimating flexibility constraints are being developed that account explicitly for physical and agronomic constraints on crop shifting. Additionally, variations in cultural costs under a variety of physical and agronomic conditions are being identified. Both these efforts are intended to improve the accuracy with which linear and separable programming techniques handle shifts in crop mixes.
2. A wider variety of irrigation technologies is being considered including six different sprinkler and three different drip systems. Additionally, a systematic effort is underway to determine the extent to which management and system design affect the efficiency with which alternative technologies apply water.
3. A number of external effects associated with savings in agricultural water and energy use are being identified and analyzed.
4. The application efficiencies of alternative irrigation technologies in the field are being measured.

5. Institutional constraints on shifting water sources are being identified and analyzed.

A major contribution of the research reported herein has been to develop methods and assess the adequacy of available data for accomplishing this larger project which has more direct relevance to the water and energy consumption faced by Californians.



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THE ECONOMICS OF WATER DEVELOPMENT  
AND USE IN CALIFORNIA

by

Donald Erlenkotter  
University of California, Los Angeles

&

Michael Hanemann  
University of California, Berkeley

&

Richard E. Howitt  
University of California, Davis

&

Henry J. Vaux, Jr.  
University of California, Riverside

ABSTRACT

The allocation of water supplies in California is in the process of transition from a "frontier" stage where the cost of new water sources results in a scarcity value for existing supplies.

The allocation of water at present is predominantly on a noneconomic basis, motivated largely by value judgments that are becoming increasingly mythological. The use of economic institutions to efficiently allocate water is proposed as an alternative to politically and economically costly augmentations to existing supplies. The cost of alternative sources of additional supply are summarized; as are the demand characteristics for the agricultural, industrial, and residential sectors. The empirical evidence available shows that water users are indeed responsive to changes in price, and that economic institutions would aid efficient allocation of constrained supplies.

The final part of the paper uses a simple two-sector model to demonstrate the economic allocation process under three alternative policy scenarios: voluntary reallocation with pricing, institutional paralysis, and water resource development regardless of cost. The model shows that the latter two scenarios are socially costly relative to economic reallocation.

## INTRODUCTION

Economics has been widely defined as "the allocation of scarce resources amongst competing and insatiable needs." This definition explains why economic methods have not been used, and rarely considered, in California water allocation decisions. In California water planning to date, economics has been regulated to an accounting procedure to measure the costs and benefits of allocations made on a political and physical basis. This approach was possibly optimal in the development state of cheap and plentiful water supplies which had no scarcity value, and thus led to little competition among competing water users.

The frontier era of California water development and allocation is over; water supplies of acceptable cost are scarce and competition between users is consequently intensifying. While it will have its costs and casualties, the new era of competitive water allocation will stimulate increased economic efficiency in water use and confer significant capital gains on those holding water rights. There is no reason to believe that water resources in California will be exempt from the changes that have characterized the prairies, forests, and urban lands when they became scarce.

The physical scarcity of existing California water supplies and projected demands is shown by a projected deficit of 2.9 million acre feet in the year 2000.<sup>1</sup> Here we analyze the alternative costs of augmenting existing supplies, which confer a scarcity value on existing supplies. If the economic process is not stifled, the rising value of water will reduce the currently projected demands and equate the economic supply and demand for water. Development of additional surface water sources may or may not be required to do this.

This paper attempts to look at the role of economics in allocating California water resources in the new "developed" era as opposed to the "frontier" era. Section II addresses some well-established beliefs about water development. By characterizing these beliefs as myths, we are not inferring they are groundless, but merely, like six gun justice, no longer applicable and socially costly to believe in. Section III views the current California water allocation method from an economic perspective, and in particular, examines the costs of additional supply augmentation and whether users will modify their water use at higher prices. Section IV uses a very simple economic model and information from Section III, to examine the outcomes of alternative policy actions represented by shifts to full or partially economic institutions for water allocation.

We are not alone in our concern for these questions. Coincidentally, the University of California Agricultural Issues Task Force<sup>2</sup> in its 1978 report identifies water as the major constraint in the future, and suggests that information is needed on "(a) possible effects on farmers of an open market pricing system for water... (b) the extent to which such a pricing system would shift water to municipal and industrial uses and (c) what alternatives to market pricing might increase flexibility of water allocation, at what costs..."

## MYTHS OF WATER DEVELOPMENT

Historically, water development and management policies have been partially based on several mythical tenets. Virtually without exception, these myths are founded on the twin assumptions that water is both unique and essential. By

assuming that water is unique, we fail to recognize that there are other resources which can be substituted for water where circumstances warrant. By assuming that water is always essential, we place on it a value that far exceeds its actual economic value. Unquestioning acceptance of these myths has caused us to both overdevelop water and to allocate it to the wrong purposes and this, in turn, has caused us to create water scarcities rather than ameliorate them. Indeed, these myths themselves have become a major part of the "water problem" since belief in them impedes objective and logical evaluation of various means for dealing with water scarcities. A careful consideration of each of these myths suggests why they should be abandoned as touchstones in the formulation of sound water policies.

### Myth I: "Water is Essential"

"For Regional Economic Development." There is widespread acceptance of the notion that water is not only required for regional economic development but that its bountiful presence guarantees such development. This myth encompasses two assumptions, one of which is false and the other which is true only in a narrowly limited sense. There is substantial evidence which shows that the availability of low cost water does not ensure that economic growth will occur.<sup>3,4</sup> One need look only at the north coast of California to find a region of abundant water with a comparatively simple and stagnant economy. Similarly, the development of an enormous water supply near the community of Oroville did not guarantee economic growth and a long-term prosperity to the residents of that community. Indeed, a predominant thrust of California water policy has been to compensate for the fact that places of population growth and economic growth are generally not coincident with places with abundant water. Thus, the fact that we have spent billions of dollars to move water from areas of origin to areas of use is testimony to the fact that water by itself is not sufficient to induce economic development.

A separate but related assumption is that economic growth cannot occur in the absence of water. Thus, it is common to point to Los Angeles and assert that it could not have grown to its present size without the development of sizable supplemental water supplies. Narrowly speaking, it is true that economic development cannot occur where there is no water at all. But this does not mean that economic growth will be choked off if water is not available in lavish amounts (as it is in the Los Angeles region). Moreover, it is unlikely that a megalopolis will arise on the Southern California desert even if water were made available in abundant amounts. Economic development is dependent not so much on the presence of water as it is on the presence of transportation facilities, the ability of the region to develop a comparative advantage in the production of goods and services for national markets, and many other factors unrelated to water.

Situations in which the lack of water is absolutely constraining on economic growth are indeed rare. The recent drought has demonstrated clearly that Marin County's water supplies are only marginally adequate. In spite of this, the citizens of that county have been struggling for years to restrain growth. A similar situation exists in the Santa Barbara area, where economic growth continues nearly unabated despite a water supply which is potentially inadequate both in terms of quantity and quality. Indeed, the drought has demonstrated just how nonlimiting available water supplies are to the economic growth of California. Despite overwhelming evidence to the contrary, we continue to believe that failure to develop new water supplies (irrespective of cost) bodes ill for the economy of California and its subregions.

For Agriculture. A related myth holds that without water there can be no agriculture. It is true that most agriculture in California as we know it could not survive without irrigation. This ignores, however, the question of whether irrigated agriculture is always the best use of scarce land and water in a semiarid region. Why, it may be asked, is irrigated agriculture the best use of scarce water supplies when the resulting yields often do not produce revenues sufficient to cover even the cost of transporting water to the field? Why should additional water supplies be developed at very high cost merely to bring new land into production, when some existing production is so marginal that it would not exist without heavily subsidized water? The basis of the myth lies with the unquestioning acceptance of the notion that agriculture has special attributes, attributes which transcend prices established in markets. Let the notion that agriculture is socially desirable is rooted in another era, an era that predates the decline of the family farm and the rise of corporate farming.

Many arguments for the need to develop new water supplies are based on the need for additional agricultural water. These arguments are myopic in that they often assume that the only remaining unused farm capacity is in California. Moreover, they ignore the potential for dryland farming and the considerable savings in current agricultural water use that could be achieved by changing water allocation rules. Why, for example, should additional water supplies be developed while some growers apply ten acre feet of water per year to citrus simply because there is no incentive for them to economize? Why should additional supplies of water be developed at substantial expense to preserve agricultural practices based on undervalued or artificially cheap water, practices which have contributed significantly to current perceived scarcities? In short, water is necessary for irrigated agriculture to prosper but it is not needed in prodigious amounts to perpetuate wasteful practices which have no justification other than historical longevity.

For Life. The most pervasive and superficially compelling myth holds that water is essential for life. Without water, we die. It is true that each person requires perhaps a quart and a half of water per day for survival. Yet on this basis, the average annual flow of the Colorado River, a river of relatively scant supplies, could support a population roughly four times that of the entire planet for a year. Inasmuch as it requires less than 10,000 acre feet annually to slake the physiological water requirements of the population of California, it is difficult to take seriously arguments that propose new water supplies as the salvation of human life itself. It is also true that humans have physiological requirements for food and shelter and yet highly expensive programs to increase the supply of steak and houses are not proposed and justified as being essential to physical survival. Current water use data indicate that, on the average, Californians use approximately 200 times more water for personal consumption than is essential. While we may prefer life styles that entail the lavish consumption of water, this does not mean that such lavish consumption is required for survival.

Myth II: "Water Development Projects Are an Appropriate Vehicle Through Which To Redistribute Wealth"

It is often alleged that water development projects are warranted, in part, because of the redistribution of wealth that accompanies their implementation. This myth suffers from a host of shortcomings, two of which stand out. First, there is no general agreement as to the proper direction and magnitude of wealth redistribution within California or the nation as a whole. In the absence of

some generally agreed upon "desired state" for the distribution of wealth it is difficult to argue that water projects or subsidized water are an appropriate way to redistribute wealth.

A second shortcoming stems from the ambiguity of the admittedly scanty evidence on the wealth-redistributing impacts of water projects and programs. Some generalizations can be made, however. Flood control projects invariably benefit the owners of flood-prone land. On the whole, landowners tend to be more wealthy than nonlandowners and there is thus an *a priori* argument that flood control programs tend to redistribute wealth toward the relatively better off. The evidence with respect to irrigation water suggests that in some instances the lot of less-wealthy growers is made better, while in other projects just the reverse is true. Subsidized recreation opportunities at reservoir sites appear to benefit people who are relatively more wealthy, since the truly poor lack the means and the income to get to reservoir sites.

Beyond these weak generalizations it is simply not possible to state--much less predict--what the wealth-redistributing impacts of water projects are likely to be. Moreover, those extolling the wealth-distributing virtues of this or that project are rarely made to analyze explicitly the impacts which they claim are so desirable. If such projects are desirable means for redistributing wealth, then at a minimum, the wealth-redistributing impacts should be made explicit.

Finally, it should be noted that in our imperfect world the problems of resolving water scarcity are difficult enough. These difficulties are manifestly compounded when we attempt to rectify unfair or inequitable wealth distribution via the same policies that we laboriously devise for ameliorating water scarcity.

There are many other means with which we are familiar that redistribute wealth clearly and effectively. At a minimum, water projects are a clumsy way to redistribute wealth, and in using them for this purpose we simply shackle ourselves in dealing effectively with the difficult problems of water scarcity.

Myth III: "Water Institutions are Unchangeable"

Our water development programs and policies are based on the assumption that the only viable alternatives to resolving our water problems are those that can be fit into the existing institutional arrangements. The result is a wasteful overreliance on technology and engineering to solve water problems. Seldom is consideration given to devising new institutions or rearranging old ones to accomplish water management objectives. By assuming that existing institutions are immutable, we often force upon ourselves solutions to water problems which are far more costly than they need to be. For years, the only effective means to control flood damages was through the construction of physical works to restrain and confine flood flows. Little note was taken of the fact that the current institutional arrangements permitted and even encouraged development of flood-prone lands which, in turn, caused flood damages to rise even higher. Only when flood damages continued to skyrocket despite the expenditure of significant state and federal monies for flood control was it officially recognized that flood damages could be significantly reduced by changing existing institutions in a way that discouraged additional flood plain settlement through use of such devices as flood insurance and flood plain zoning.

Groundwater is another pertinent example. Efforts to devise effective institutional arrangements for the unified management of groundwater are opposed as an unwarranted political intrusion on the economic freedoms of individuals.

...the institutional history of other resource... which private enterprise is treasured. The petroleum... institution, has long touted the virtues of private enterprise and... proposals entailing even a modicum of outside control... regulation. Yet, when faced with potentially ruinous exploitation of its... resource base, the members of the industry supported and even... demanded new institutional arrangements designed to ensure the orderly... exploitation of the resource. This resulted in the establishment of a number... of governmental institutions which control rigidly, through unitization and... prorationing, the quantity of oil which each operator is permitted to pump. In... many areas, we face similar potential ruination of our groundwater resources, but the lesson from the oil industry is lost because of our unwillingness to consider institutional change as a viable way of resolving some of our water management problems.

Certainly innovative institutional arrangements are not always superior to development alternatives that take the existing institutional arrangements as fixed. The converse is not true either, however, as institutional rearrangements are often more efficient and preferable in other ways to structural measures for the development and allocation of water. Often, it is argued that since institutional arrangements result from political forces, considerations of efficiency and economy are inappropriate. Inherent in this argument is a failure to understand that political demands for augmentation of water supplies, or reallocation of existing supplies are motivated by forces that are predominantly economic. This is because conventional economic markets often fail to yield the incentives for production and allocation of water that they do with other commodities. When markets frustrate legitimate economic forces, it is usually the case that those forces work themselves out through extra-market institutions. Increasingly, it has become the job of government to devise and operate extra-market institutions to meet certain economically-motivated demands of society. In these instances, considerations of efficiency and economy are every bit as relevant as they are to more conventional economic institutions. To argue otherwise is to misunderstand the inherently economic forces leading to demands for political action.

#### Myth IV: "Droughts and Floods are Acts of God"

There is a widespread tendency to view droughts and floods as phenomena over which we have no control. The response to droughts and floods then tends to be an ad hoc response, taken at a time when the event is upon us and when our flexibility to deal with it is most severely constrained. The response, which is usually to provide relief and assistance to the victims, follows directly from the misplaced belief that we are helpless in the face of complete uncertainty over the time of such personally catastrophic events as illness and injury and even death. The difference is that we treat these events as contingent events rather than as acts of God and protect ourselves accordingly through contingency claims or insurance. It is important to note that we would have no incentive to do so if there was some certainty that government would defray all costs associated with contingent events through relief and assistance. If we regard droughts and floods similarly as contingencies rather than as acts of God, we not only minimize the damages from such events, we prod individuals who may be affected to think and plan for the contingent event ahead of its actual occurrence. In this way, the range of options that can minimize the impact and otherwise protect against droughts and floods are broadest. A system of disaster insurance would enable us to deal with contingencies associated with water supplies in the same fashion that we deal with other contingencies of life.

All these myths are rooted in the notion that water is different, different from other resources that enhance our well-being. While water does have unique locational and physical properties, as an economic resource it is no more unique than wildlife or petroleum or timber. In short, there is no more a case for being careless and wasteful in the development of our water resources than there is a case for being careless and wasteful in the production and allocation of petroleum, automobiles, clothing or shelter. If we are to be as successful in producing and allocating water as we have been in producing and allocating other commodities that are important to our welfare, we need to view water as an economic commodity rather than as some different magical substance that requires myths, incantations and appeals to higher principles for effective management.

## ECONOMIC POLICIES FOR SCARCE WATER SUPPLIES

### The California Water Allocation System

The existing water allocation system in California is a potpourri of organizations, laws, rules, regulations, traditions, customs and other institutions. A visitor sent from outer space to examine it might conclude that it possessed a sample of virtually every institution known on this planet. He would be amazed that the system works at all and perplexed at the resistance to even modest changes that would cause it to work far better than it does now. If that visitor looked at our more traditional economic allocation systems, he would probably depart shaking his head at the inconsistency between these systems which reward efficiency and penalize waste, and the water system where efficiency is not demanded and waste is sometimes encouraged.

Property rights are a fundamental basis for any allocation system. Generally speaking, clear-cut property rights with a minimum of contingencies result in allocation systems in which scarce resources are devoted to their highest valued or most efficient uses. In California, water rights are derived from an admixture of no less than three different systems of property rights. A full review of the range and problems of California water rights is given in the Final Report of the Governor's Commission to Review California Water Rights Law.<sup>5</sup> However, some of the main institutional barriers to economic methods of demand management are briefly reviewed here.

(a) Groundwater in California is rarely adjudicated and is invariably held by correlative rights of overlying landowners for reasonable use. This common property institution contains no incentive for prudent or efficient use. Groundwater users are in the same position as children receiving candy on Halloween, if they don't take it, someone else will and the opportunity may not come again. The effective marginal price of groundwater is the variable pumping cost, which is relatively low in the majority of regions.

(b) Riparian water rights are an archaic and noneconomic institution that may be extremely costly to change. Understandably those who hold them are most reluctant to relinquish these valuable rights.

(c) Appropriative rights encompass a large proportion of California's water rights; the exact nature and restrictions on these rights have been delineated by several court cases on what constitutes "beneficial use." Currently this interpretation does not encourage attempts to transfer water to

more efficient uses by means of sales. The Governor's Commission Final Report recommends a more exact specification of conditions under which appropriate rights can be traded and transferred.

Superimposed on these state rights is a system of federal rights whose relationship to the state rights is not always clear. Moreover, some federal rights are only implied, and it will take years of litigation to clarify them. The allocative system, then, is hamstrung from the beginning by confusion and uncertainty surrounding the conditions of ownership and the conditions of use. Much effort is devoted to costly and time-consuming litigation to reduce this uncertainty and confusion.

Virtually no provision is made in California water law for the transfer of water rights and this impedes efficiency by locking water into relatively low valued historical uses. In some instances, the nonuse of a water right may be grounds for forfeiture. This "use it or lose it" proviso creates incentives to use excessive quantities of water or to devote it to clearly submarginal uses in order to avoid forfeiture. The proviso also impedes temporary transfers of water by fostering a belief that a user who transfers a right on a short-term basis may lose the right altogether due to nonuse. In this fashion, the complex and imperfect system of water rights in California creates inflexibilities in both short- and long-term allocation, and contributes directly to the inefficient and wasteful use of water.

The patchwork and inconsistent use of prices is also characteristic of the California water allocation system. While prices are sometimes used to allocate municipal and industrial water, they are almost never used to allocate agricultural water. In many instances, agricultural water prices do not even accomplish the function of recovering the costs of developing and conveying supplies. Agricultural water prices vary greatly and with very little relationship to location. Thus, two different growers raising the same crop equally far away from their water sources may pay very different prices for their water. It is not uncommon for this price differential to be explained solely by the fact that the water is being supplied by different organizations. In these situations, price differences are not reflective of differences in the cost of supplying water, the willingness to pay for water or the scarcity value or rent attributable to water.

Other price distortions abound. Groundwater, although scarce, is not priced at all. Rather, the charge paid by groundwater users is for energy and facilities needed to pump and convey it. In some instances, prices are established by long-term contracts and cannot be changed to reflect changing cost conditions or changes in the value of water. In others, water is priced simply to cover the costs of conveyance. Here, the price paid by an individual user may be largely a function of the number of consumers being supplied by a given water purveyor. The price of water thus bears no relationship to its value. In still other instances, water is made artificially cheap by charging prices which correspond to the average cost of supply. Users are not confronted with the real marginal cost of supply and therefore tend to use more than is economically justified. In certain areas, some of the costs of water supply are defrayed by power consumers, resulting in distortions in both the price of water and the price of energy.

There are also discrepancies between prices charged for agricultural water and those charged for municipal and industrial uses. Municipal and industrial prices are usually established prior to the time water is sold and used. Users can respond to these prices in deciding how much to take. Agricultural water prices, on the other hand, are often developed after use and consumers can only estimate what they might pay when making their consumption decisions. This is not to imply that municipal and industrial pricing practices are without fault. Large amounts of municipal water are purveyed by public utilities or similar organizations whose pricing policies are directed solely at recovering the average cost of supply. So single-minded is the devotion of these organizations to cost recovery that they fail to recognize that costs need to be recovered only in the long-run. They consequently neglect the fact that in certain short-run situations it is efficient to ignore fixed costs and recover only the variable costs of operation. Thus, during the drought, certain citizens were treated to substantially higher costs for water occasioned by their good faith in reducing water consumption in response to pleas to conserve water during a time of severe shortage. Distortion in water pricing mechanisms similarly led to the drought-induced spectacle of people in the arid southern portion of the state using water to clean sidewalks and driveways while their compatriots in the moister north suffered sharp restrictions in the amount of water available for basic household needs.

Finally, the water allocation system in California is characterized by a degree of intergovernmental and organizational heterogeneity that sometimes defies the imagination. The federal government has no less than six major agencies with responsibility for differing components of the water allocation system. The functional and operational responsibilities of these agencies are not always clear-cut and are often the subject of controversy. The two major state agencies with water allocation responsibilities, the Department of Water Resources and the State Water Quality Control Board, are often in conflict with each other and with the federal agencies. Added to this are a multitude of local governmental agencies ranging from arms of local general government to special district governments formed for the sole purpose of acquiring and supplying water.

There are literally more than a thousand governmental agencies with water allocation responsibilities, all vying with each other and with their respective constituencies over issues that importantly affect the allocation of water within California. The agencies are guided by different rules and different perspectives with the result that many important water allocation decisions are made via bargaining processes, processes in which factors other than efficiency of use and avoidance of waste often predominate. The allocation of water among uses and users emerging from these bargains usually differs sharply from the economic ideal.

A proliferation of organizations per se is not inherently undesirable in an economic sense. What is undesirable is the lack of efficient and effective coordinating mechanisms. This lack of coordination contributes to uncertainty over ground rules, and leads to a confusion of ends and means, and to needless conflict that does nothing but distract attention away from the fundamental problem of allocating scarce water resources.

This short review of the existing water allocation system in California suggests that three features dominate. First, there is an imperfect system of water rights which creates uncertainty and impedes the allocation of water to its highest valued uses. Second, there is a system of distorted prices, prices that often fail to reflect the cost of supplying water and, in agriculture,

TABLE 1  
Estimated Costs of New Water Supplies for California

Source	Unit price	Quantity
<u>New Surface Development</u>		
	\$100-\$300 per acre foot. (average = \$160 per acre foot)	3.30 million acre feet
<u>Groundwater Storage</u>		
Central Valley	\$30-\$100 per acre foot (average = \$50 per acre foot)	0.10 million acre feet
Southern California	\$30-\$150 per acre foot (average = \$70 per acre foot)	0.15 million acre feet
<u>Municipal Wastewater Reuse<sup>b/</sup></u>		
Plant capacity		
2 million gallons per day	\$160 per acre foot	1.80 million acre feet
10 million gallons per day	\$100 per acre foot	1.00 million acre feet
100 million gallons per day	\$72 per acre foot	1.00 million acre feet
<u>Desalination<sup>c/</sup></u>		
Seawater		
Distillation	\$788 per acre foot	-- <sup>d/</sup>
Freeze	\$341 per acre foot	--
Membrane	\$1,502 per acre foot	--
Brackish water		
Freeze	\$485 per acre foot	N/A <sup>e/</sup>
Membrane	\$355 per acre foot	N/A
Electrodialysis <sup>f/</sup>	\$283-\$466 per acre foot	N/A

a/ All costs in 1977 dollars.

b/ The estimates of quantities potentially available are for 1990 and are based on the Department of Finance Series S-O Population Projections. The estimates are also based on the assumption that all municipal and industrial water not consumptively used is available for reuse.

c/ Desalination cost estimates are modifications of estimates originally prepared by Fluor Engineering for the Office of Water Research and Technology, Department of the Interior.

d/ Supplemental quantities of water available from seawater desalination are theoretically limitless. Most sources agree that the high cost of seawater conversion will limit quantities actually produced to something less than 0.10 million acre feet for California.

e/ N/A = not available.

f/ Electrodialysis is cost-sensitive to the salt concentration of the feedwater. The low estimate assumes a feedwater salinity of 1,800 parts per million or less while the high estimate assumes a salinity of 3,000 parts per million.

Surface Supplies. Preliminary estimates of the unit cost of water and the probable size of service supply augmentation have been obtained from the Bureau of Reclamation and the California Department of Water Resources. These estimates are for facilities not currently authorized for construction and for which detailed design information has not been developed. The estimate indicates that perhaps as much as 3.3 MAF could be made available at unit costs ranging from \$100/AF to \$300/AF. The average unit cost of water from all facilities

almost always fail to reflect its value in use. Third, there are numerous federal, state and local organizations with responsibility for the development and allocation of water supplies. These organizations have overlapping and sometimes conflicting responsibilities. Their effectiveness is severely compromised by a lack of efficient mechanisms to coordinate their diverse activities. Examined as a whole, all three of these features appear to have been developed in an ad hoc fashion. These institutions have been built over time by making numerous incremental modifications designed to account for new circumstances as they arose. The result is an institutional patchwork of often anachronistic laws, prices and organizations inappropriate for the allocation of scarce water in an advanced industrial age.

### Economics of California Water Supply Augmentation

Traditionally, California water policies have focused almost exclusively on the need to develop new water supplies in the face of increasing demands for water from both agricultural and urban users. These policies have often been criticized on the grounds that they are inefficient and exacerbate the inflexibilities inherent in the "water industry." Despite these criticisms, development of costly new sources of water has continued. What is different about the current water policy setting, is the increasing acceptance of the fact that the costs of developing still more new water supplies are becoming unacceptably high. That the costs of developing new water supplies are increasing and will continue to increase is beyond dispute. Low cost sources of water have already been exploited. The remaining supply augmentation possibilities are more difficult to exploit and therefore more costly. Add to this a prolonged period of sharp inflationary pressures and increases in the relative prices of inputs necessary to develop new water supplies, such as energy and concrete, and it is hardly surprising that the costs of new water sources are skyrocketing. In this connection, an examination of the probable range of costs of new water supplies is instructive.

In Table 1 a range of costs are presented for four categories of supply augmentation possibilities. These supply possibilities do not include the Peripheral Canal and related projects, for which there is some uncertainty over the portion of costs allocable to preservation of environmental quality. Care must be exercised in interpreting these estimates. They are not representative of the precise costs likely to prevail, but rather are the best estimates based on currently foreseeable and anticipated conditions. The historical record demonstrates that the forecasting of water costs is fraught with inaccuracies and that there is a pronounced tendency to underestimate actual costs. Additionally, water costs are extremely sensitive to variations in both time and location. Any attempt to estimate such costs on a statewide basis must therefore suffer from a lack of precision. It is probably true, however, that costs substantially lower than those presented in the table are not likely to be realized. A few low cost supplies may be found and developed but the magnitude of these supplies is likely to be so small as to be an insignificant portion of the total state supply.



would be \$160/AF. These estimates do not include the costs of conveyance from either the Sacramento River or the Delta. This means that the cost of water at the site of use will be higher than the costs reported in the table and significantly so if substantial pumping or construction of new conveyance facilities is required.

Groundwater Storage. The estimated costs of additional groundwater supplies are long-run costs for groundwater storage. The estimates include the costs of conveying water to the storage site and pumping. The estimates do not include the cost of moving water from the wellhead. Conveyance and pumping costs range from \$30 to \$150 per acre foot with an average of between \$50 and \$70 per acre foot, depending upon the site. While these costs appear relatively attractive, it should be noted that current estimates suggest that no more than an additional 250,000 acre feet per year could be made available through groundwater storage. The costs of yet more supplies from groundwater storage would be substantially higher.

Municipal Wastewater Reuse. The reuse of municipal wastewater represents a potentially new source of supply throughout California. The unit cost figures suggest that economies of scale in wastewater treatment are crucial in determining unit cost. Each of the estimates is for the cost of water at the plant boundary. Conveyance costs prior to and after treatment are not included and these will increase the reported estimates significantly. The relative cost attractiveness of water produced from large-scale wastewater treatment plants is somewhat deceptive. Currently there are fewer than ten areas in the state where the population is dense enough to warrant construction of extremely large treatment plants. A substantial portion of the municipal wastewater in California would have to be treated in significantly smaller plants with attendant increases in cost. Moreover, efforts to consolidate wastewater treatment facilities to realize economies of scale must account for increases in the costs of conveying wastewaters to the treatment plant, and these costs may tend to offset gains realized from economies of scale.

The costs of treated municipal wastewater may also be understated in comparison with other costs included in the table due to water quality considerations. These figures do not reflect costs that may have been incurred for any special treatment occasioned by the need to deal with viruses or heavy metals. On the other hand, should all communities be required to install secondary wastewater treatment irrespective of final use, as stipulated by the water quality amendments of 1972 (P.L. 92-500), the reclaimed wastewater costs reported here would be significantly lowered. In addition, the estimates of the quantities of water potentially available from wastewater are probably high. The estimates in the table are based on the assumption that all municipal and industrial wastewater not consumptively used in California in 1990 will be available for reuse. It should be recognized that the expense of conveyance will probably constrain the quantities of water actually available for reuse to amounts considerably less than those reported in the table.

Desalination. It is often stated that the promise of technology will ultimately relieve us of any binding water scarcity, and no technology has been held more promising than desalination. Seawater conversion, it is argued, can rid us of our dependence on freshwater sources by making the seas themselves important sources of supply. Despite nearly 30 years of intensive research and development in seawater conversion technology, the current cost picture is far from attractive. The costs reported are at the plant boundary. No estimates have been made of the potentially significant conveyance and pumping costs.

With the advent of sharply increasing energy costs, distillation technologies have become so prohibitively expensive that they are seriously considered only in locales or regions with virtually no alternative sources of supply. Technologies that rely on freezing processes are also extremely costly and their commercial feasibility has not been fully proven. Membrane processes for seawater conversion are the most expensive of all. Nor is the promise of additional technological development especially bright. Estimates made by Fluor Engineering indicate that an investment of nearly \$150 million over the next ten years could reduce distillation costs by 30 percent, freeze costs by 40 percent and membrane costs by perhaps as much as 70 percent.<sup>6</sup> If these estimates should prove accurate, seawater still could not be converted for less than \$300/AF. Moreover, a doubling of energy costs over this same ten-year period would probably offset the savings gleaned through technological gain.

The estimated costs of brackish water desalination are somewhat lower, although still extremely high. Here, too, costs are estimated at the plant boundary with no allowance for conveyance costs. The costs of desalting brackish waters are in line with current estimates of costs for desalting agricultural return flows. Investment of \$30-\$40 million over the next decade could bring the costs of freezing and electrodialysis down between 40 percent and 50 percent if there are no offsetting increases in energy prices. An investment of \$42 million in membrane technology might bring the cost of desalting brackish water slightly below \$100/AF but only if energy costs remain constant. The magnitude of costs of desalting brackish water suggests that without unanticipated technological breakthroughs, desalting is likely to be attractive only in certain unique situations. Brackish water conversion is not likely to yield additional freshwater supplies on a scale which would have any statewide significance.

All these cost estimates suggest that substantial new water supplies are not likely to be available for California at less than \$100/AF. In all likelihood, the costs will be considerably greater. In order for these various supply augmentation possibilities to be economically attractive, it is necessary for individuals or groups to be willing to pay at least the unit cost of production over the long term. We turn next to a discussion of the willingness to pay for water in California.

#### Economics of Water Demand Management

Much of the literature on water policy is couched in terms of water "requirements" or "needs." This perspective has led to great efforts in planning alternative ways to supply water with little questioning of the need. However, this terminology is misleading and should be abandoned: the current level of water consumption in California is so high that the physical survival level becomes entirely irrelevant. Instead, we take the view that water is a commodity just like other commodities which are allocated through some form of market mechanism. The major difference between water and other commodities lies in the nature of the market for water which, in California, relies on prices for allocation only to a limited degree and tends to be in permanent disequilibrium because of the inflexibility of procedures for market adjustment. Accordingly, as with other commodities, we shall refer to water demands rather than needs.

The actual level of water consumption is determined by the interaction of demand and supply factors. Table 2 shows the growth in consumption of fresh water statewide and the changing shares of agricultural and urban uses over

TABLE 2  
Freshwater Withdrawals in California  
(million acre feet)

Water use	1950 (1)	1950 (2)	1955 (3)	1960 (4)	1965 (5)	1967 (6)	1970 (7)	1972 (8)	1977 (9)
Agricultural	19.0	23.3	25.9	28.5	28.2	31.2	37.2	31.7	35.5
Urban	1.7	1.8	2.7	3.3	6.2	4.4	6.0	5.0	5.5
TOTAL	20.7	25.1	28.6	31.7	34.4	35.6	43.0	36.7	41.0

Sources: (1) Department of Water Resources, Bulletin No. 3, May 1957.

(2) USGS, Circular No. 115, May 1951.

(3) USGS, Circular No. 398, 1957.

(4) Department of Water Resources, Bulletin No. 160-66.

(5) USGS, Circular No. 556, 1968.

(6) Department of Water Resources, Bulletin No. 160-70, December 1970.

(7) USGS, Circular No. 676, 1972.

(8) Department of Water Resources, Bulletin No. 160-74, November 1974.

(9) Proceedings of the Governor's Drought Conference, March 7-8, 1977, Los Angeles, California.

the past 30 years. One feature of the data is immediately apparent--there are substantial differences between state and federal estimates which, to our knowledge, have not been reconciled. According to the state data, the consumption of fresh water has risen from about 21 MAF in 1950 to about 41 MAF in 1977; the share of urban use has risen over this period from 8.2 percent to 13.4 percent. As a first approximation, it may be said that the secular increase in agricultural consumption has been due primarily to shifts in supply associated with the development of the State Water Project and the Central Valley Project, while the secular increase in urban consumption has been due primarily to shifts in demand associated with the growth in the state's population. In the remainder of this section, we will focus on the factors influencing demand in agricultural and urban uses.

The Concept of a Demand Function. When economists talk about the demand for a commodity, they usually distinguish between a final good and an intermediate good. A final good is essentially a commodity consumed directly by individual consumers; an example is the residential use of water. An intermediate good is a commodity which is used as an input in the production of some other good; examples are the agricultural, industrial and commercial uses of water. The factors influencing the demand for each type of good are slightly different. For a final good, the factors are the price of the good, the price of other goods, the consumers' incomes, and their tastes. In the case of residential uses of water, the factors which influence tastes would include climate, household composition, and the type of housing (multifamily versus single family, lot size, etc.). For an intermediate good, economists refer to the "derived" demand for the good, since the demand for the good is derived partly from the demand for the commodity in production of which it serves as input. Given the demand for the output commodity, the demand for any particular input depends on the price of that input, the price of other inputs, the level of output, and the technology of production. In the case of the agricultural use of water, the technology depends partly on climate and soil conditions; in the case of industrial and commercial uses, it depends partly on factors such as the age of the plant.

Although many factors influence the demand for a commodity, economists are frequently interested in the effect of price on demand. This is especially relevant for a commodity, such as water in California, where the question of using prices to reallocate existing supplies is a major policy issue. The effect of price on demand is represented graphically by a demand curve, a plot of the quantity demanded versus price, holding all other factors constant. For a normal commodity the quantity demanded varies inversely with the price (the demand curve slopes down); the residential, commercial, industrial, and agricultural uses of water would all fall into this category. It is common to summarize the responsiveness of demand to price in terms of the "price elasticity of demand," which is defined as the ratio of the percentage change in quantity demanded to the percentage change in price. An elasticity of minus unity implies that a ten percent rise in price, say, would bring about a ten percent reduction in the quantity demanded. An elasticity of -1.5 implies that the same price rise would induce a 15 percent reduction in the quantity demanded; an elasticity of -0.5 implies that the same price rise would induce only a five percent reduction in the quantity demanded. If the elasticity of demand for a commodity is below unity, the demand is said to be inelastic; the limiting case is an elasticity of zero, where there is no change in the quantity demanded when the price changes. If the elasticity of demand exceeds unity, the demand is said to be elastic; there is no upper limit on the possible elasticity of demand in this case.

The price elasticity of demand--that is to say, the responsiveness of demand to price--depends on the slope and curvature of the demand function, which is entirely an empirical question. Depending on the formula for the demand curve, the elasticity may be constant or it may vary with the level of demand.

We must emphasize that the magnitude of the elasticity of demand is an empirical matter: some of the evidence on elasticities for agricultural and urban uses of water will be presented below. Nevertheless, economic theory can shed some light on the factors which cause the elasticity of demand to vary in the case of an intermediate good. Firstly, consider a farm or a firm producing a particular type of output which requires water as an input. It can be shown that the demand for an input is more elastic: (a) the more readily other inputs can be substituted for that input, (b) the larger is the share of the input in the total cost of producing the output, and (c) the more elastic is the demand for the output which is being produced. At very low prices, the cost of water as an input is so small in relation to the total cost of production, that a producer will scarcely alter his use of water when price changes (one can argue that this was true of prices for agricultural uses in the mid-1960's and 1970's). At high prices, this may no longer be true. In this connection, it is interesting to compare industrial and agricultural uses of water as an input. In industrial uses the cost of water is a minute portion of the total cost of production--generally well under two percent.<sup>7</sup> In agricultural uses the cost of water is frequently a substantial portion of total cost--around 20 to 25 percent for vegetables and some fruits and almost 50 percent for some field crops.<sup>8</sup>

Thus far, we have assumed that a particular type of product is being produced and the response to a change in input prices takes the form of changing the input mix and/or the level of output. Now assume that the farm or the firm can alter the mix of outputs (crops or product lines) which it produces. This provides an added dimension of response to input price changes--a switch from more water-intensive outputs (crops) to less water-intensive ones. To the extent that the output mix is variable, there is a greater elasticity of demand for the water input. This is about as far as pure theory can take us. We now turn to the empirical evidence on the demand for water in agricultural and urban uses.

The Demand for Agricultural Uses. Agricultural water use comprises 86 percent of total water use in California, and therefore the pricing of agricultural water is a key policy issue. In this context a knowledge of the price elasticity of agricultural demand is of the utmost importance. If the demand were extremely inelastic, it would be pointless to rely on pricing to ensure a correct allocation of available water supplies both within the agricultural sector and between agricultural and urban uses: higher prices would penalize users without inducing any change in the pattern of water use. If the demand is not totally inelastic, pricing is a viable tool for reallocating water supplies and ensuring their efficient use.

Casual observation suggests that the agricultural use of water does respond to price. A farmer can always change the average use of water per acre by adjusting the cropping mix. Admittedly, the flexibility available to the farmer depends on the long- or short-run nature of the adjustment. However, the recent California drought showed that farmers, even in the short run, are adept at weighing the relative profitability per unit of water used and, at certain water prices and scarcities, they reduce the acreage grown of less-favored crops. The price that the farmer expects to get for the crop

and the cost of other inputs needed to grow the crop enter into the decision of how much a farmer is willing to pay for the water. Moreover, at high water prices, it may be worthwhile to shift to more expensive irrigation technologies that allow more acres to be grown with the same amount of water. Where water prices are very high and the land less productive than the average, the farmer may make the most money from dryland crops or preirrigated barley.

Since agriculture is a business sector like any other, the water policy analyst should not bow to all requests from the industry, since every sensible producer wants the cheapest possible inputs. Rather, the analyst should take the position of the farmer and ask, "How would I react to this policy?" In this way, the analyst has a better chance of determining what will happen and how the incomes of farmers and the consumers of their products will be affected. Unfortunately, people will always tell you, often loudly, of the "needs" but rarely reveal their demand functions.

Since water allocation by pricing mechanisms depends on the demand being elastic at water prices to be charged in the near future; what empirical evidence is there available? In agricultural uses, unlike many urban uses, farmers do not necessarily know the price of their water input at the time when they make their input decisions. Retail agricultural water districts and cooperatives often determine their charge for water ex post at the end of the season--they calculate operating costs retroactively and set the commodity charge roughly at average cost in order to balance their budget. Due to the essential absence of a market for irrigation water in most regions, empirical estimates of the agricultural demand for water have to be based on normative studies. In this type of approach a computer model is built of the agricultural sector studied. The model assumes that farmers act to maximize their profits, and is verified against current cropping actions, water use and yields. The model is then used to estimate how farmers would change their operations to maximize profits under higher water prices. The results under several higher prices yield a demand function for water, whose elasticity can be measured at various prices.

The most recent empirical study of the demand for agricultural water in California is based on all the nonperennial crops grown in the Central Valley areas.<sup>9</sup> These crops tend to have a more elastic demand for water than the omitted perennial crops.

The precise estimate of the elasticity depends on the free market price for water. Over the next decade this is most likely to fall in the \$25-35 range (in real terms). However, it should be emphasized that because of pricing rigidities the actual water rate that most farmers will pay will be lower. The results in Table 3 show that farmers are indeed price elastic in their demand for irrigation water in this price range. This is encouraging news because it suggests that if the pricing process is not distorted, the water supply and demand will be to some extent self-regulating. In short, as water prices rise, farmers will modify their demands for the large quantities of low productivity water projected as "needs" at lower water prices.

Table 3<sup>a</sup>

Price per acre foot (1976 dollars)	Price elasticity of demand
\$25-\$35	-1.502
\$35-\$45	-0.462

a/ See footnote 9.

The Demand for Urban Uses. The data on Table 2 show that urban uses constitute a small but growing share of total freshwater consumption amounting to perhaps 5 MAF per year. To this should be added withdrawals of brackish and saline water by urban users--primarily by industrial users for cooling which the Census of Manufacturing estimates at around 0.7 MAF for manufacturing industry in 1973, plus an additional 9.2 MAF for thermoelectric power generation according to a U.S. Geological Survey (USGS) estimate for 1970.<sup>10</sup> Urban uses may be divided into four categories: residential use; public use for services provided by a municipality to its residents, such as fire fighting, street washing, irrigation of public parks, etc; commercial use; and industrial use including manufacturing industry and thermoelectric power generation. The first three uses are almost entirely met by water purchased from a publicly or privately owned water company; industrial users supply about 56 percent of their own freshwater intake and all of their brackish water intake.

It is hard to calculate the breakdown of urban water use among these categories because of discrepancies in the available data, especially data on industrial water use. In particular, there are substantial discrepancies between the estimates published by the California Department of Water Resources (DWR) and federal government agencies. For example, the DWR estimates of urban freshwater use pertain to gross use for most uses but to net (consumptive) use for power plant cooling, while the USGS estimates pertain consistently to gross use. This explains why the USGS estimates of total urban use of freshwater are much higher than the DWR estimates in Table 2. There are also differences in the estimates of water consumption in manufacturing, although in this case, the state estimates are higher than the federal estimates; these are shown in Table 4. Whereas the Census of Manufacturing estimates the intake of freshwater by manufacturing firms in 1959 at .45 MAF, the DWR estimates the average annual intake of freshwater at .92 MAF for the years 1957-1959; similarly, the Census has an estimate of .71 MAF for 1968 and .66 MAF for 1973, while DWR has an estimate of .95 MAF for 1970.<sup>11</sup>

Although the numbers differ, both the Census and DWR data point to a significant decrease in the manufacturing intake of freshwater since the late 1960's, following a decade or more of increase in intake. This contrasts with the continuing growth in manufacturing output: between 1968 and 1973 the value added by California manufacturing firms using 20 MG of water or more grew by about five percent in constant dollars. In order to standardize for the effects of output changes, we have calculated the amount of water intake (in MG) per million dollars of value added (in constant 1967 dollars) based on the Census data. This is shown in Table 5. For California manufacturing industry as a whole, the intake of freshwater fell from 25.3 MG per million dollars of value

added in 1968 to 22.4 in 1973, after having been roughly constant for the preceding decade. The total intake (freshwater plus brackish water) rose from 39.7 MG per million dollars in 1968 to 44.7 in 1973, after having fallen steadily over the preceding decade. The rate of water recirculation for the manufacturing sector as a whole, which was 3.7 times in 1959 and 1964, rose to 4.1 in 1968 but fell back to 3.8 in 1973.<sup>12</sup>

What can explain these changes in manufacturing water use? Among the factors which have been suggested are changes in the quality and type of raw material inputs, changes in the design of manufacturing plant, and the introduction of more efficient industrial processes. However, these changes are not necessarily exogenous: they may have been induced by changes in input or output prices. Since we do not have any systematic data on the cost of water inputs for California manufacturing firms, it is not possible to estimate the influence of changes in these costs, but they probably had a significant effect. A related, and very important, factor has been the introduction of pollution control regulations since the late 1960's, which substantially raised the effective cost of using and discharging water and forced firms to rethink their approach to water use.

What of the changes in the other components of urban water use? Population growth and the rise in per capita incomes have undoubtedly played a major role in the growth of residential, commercial and perhaps public uses. As for water prices, it is difficult to comment on the role which they may have played in moderating the growth in residential and commercial water use because of the lack of data on price levels. However, we can offer some general comments on water pricing. Most commercial (and publicly supplied industrial) water use is metered; for residential use the proportion metered is somewhat lower. It has been estimated that about 90 percent of California's population resides in metered areas. The nonmetered areas are found in parts of the Central Valley and in the outlying parts of the state. The introduction of metering by itself generally leads to a significant one-time reduction in water use. The rest of the effect depends on the type of charge scheme. Most charge schedules are based at least partly on actual water consumption. There is usually a minimum service charge with an allowable unit of water use, followed by one or more rate blocks. In most cases these blocks are charged for at a declining rate but recently a trend has begun towards having a constant commodity rate.

For the water allocation model presented in Section IV it is necessary to have some estimate of the price elasticity of demand for urban water use. All the available evidence suggest that this varies by type of urban use. It appears that public use is the least price responsive, since cities normally supply their own water: the presumption is that for public uses cities employ "as much water as is needed." The largest amount of statistical evidence on the price responsiveness of water use pertains to residential use. The bulk of the evidence suggests a residential price elasticity in the range -0.3 to -0.4, with a substantially higher elasticity (perhaps double) for summer sprinkling use if this were charged for separately.<sup>13</sup> We know of only one study which focused specifically on commercial demand, and this yielded an elasticity of -1.04.<sup>14</sup> There is a small number of studies of the elasticity of demand in individual sectors of manufacturing industry, which generally yield estimates in the range -0.7 to -1.4.<sup>15</sup> For the manufacturing sector as a whole it would probably be reasonable to postulate an elasticity roughly similar to that for the commercial sector--i.e., about -1.0.

TABLE 4  
Intake of Water by California Manufacturing Firms  
(million acre feet)

Water use	1954	1959	1957-59	1964	1968	1970	1973	1977
Freshwater	N/A <sup>a/</sup>	.451	.917	.565	.710	.947	.661	N/A
Brackish and salt water	N/A	.528	N/A	.500	.406	N/A	.659	N/A
Total intake	.976	.979	N/A	1.065	1.116	N/A	1.320	1.378

a/ N/A = not available.

Source: 1954, 1959 - 1959 Census of Manufacturing, Vol. 1, Tables 11-6, 11-7.

1957-59 - DWR, Bulletin No. 124, Table 7.

1964 - Census of Manufacturing, Vol. 1, Tables 2C, 3B.

1968 - Census of Manufacturing, Vol. 1, Tables 2, 3.

1970 - DWR, Bulletin No. 124-2, Table 7.

1973 - Census of Manufacturing, p. SR4-56.

1977 - Bennenson (1977), Table 7, see footnote 17.

TABLE 5  
Total and Freshwater Intake per Unit of Value Added, California Manufacturing Firms  
(million gallons intake per million dollars value added, in 1967 dollars)

Specific industry code	Industry	Total intake				Freshwater intake			
		1959	1964	1968	1973	1959	1964	1968	1973
20	Food	56	56	56	118	46	42	45	41
24	Lumber	137	295	388	347	128	295	388	347
26	Paper	248	271	365	380	176	213	321	302
28	Chemicals	N/A <sup>a/</sup>	109	75	69	N/A	70	57	37
29	Petroleum and coal	N/A	317	256	268	N/A	66	74	83
32	Stone, clay, and glass	84	78	74	53	32	32	38	N/A
33	Primary metals	33	41	36	66	30	24	25	N/A
All manufacturing		54	43	40	45	25	25	25	22

a/ N/A = not available.

Source: Intake and value added from Census of Manufacturing. Value added deflated by the National Wholesale Price Index for each sector.

Economic Policies for Demand Management. It is important in discussing demand management to distinguish between movements up or down a demand curve and shifts of a demand curve. In the first case the water users do not change their preferences or technology but react (in a profit maximizing way, for a derived demand) to water price changes along their demand function. In the latter case, when the demand function shifts this implies that the technology or preferences underlying the demand have changed and at the same price the water user will demand a different quantity. We will refer to policies designed to effect an inward shift of the demand curve as *conservation measures*, and to policies designed to effect a movement along a demand curve as *demand management measures*.

From an economic point of view the existence of unexploited but socially beneficial opportunities for shifting the demand curve inward via conservation measures is a symptom of the occurrence of some form of market failure, since otherwise these opportunities would have been exploited. In fact there is ample evidence of the presence of market failure in the allocation of water resources, and a considerable number of opportunities for water conservation have been identified. In the case of residential uses these involve changes in both consumer preferences and the technology of water use in the household. In the case of commercial, industrial and agricultural uses of water as an intermediate input, these involve primarily changes in the technology of water use and improved practices within the current technology set. The problem arises in that many of the alternative technologies to some degree substitute energy or labor use for water savings and face the rising costs and scarcity of both of these inputs. For example, in agricultural water use most feasible water conservation technologies would not be adopted by profit conscious farmers at current relative prices.<sup>16</sup> Moreover, unlike low-flow shower heads, the expensive irrigation technological changes do not appear to be worth subsidizing. By contrast, residential and perhaps industrial uses seem to offer greater promise for implementing conservation measures.<sup>17</sup>

As we have defined it, demand management means changing the quantities of water that users consume by changing the effective price, thus ensuring that in any sequence of years the quantities available for supply equal the quantities demanded. A simple free market for a single commodity, say avocados, allows trading to continue until the supply and demand for avocados is equated in each year despite annual surpluses or scarcities. With California water supplies the situation is not that simple. Water agencies and water users, especially in the agricultural sector, have to be able to plan and contract years ahead in some cases, while the supply is composed of many diversified sources and water rights. Economists in advocating market systems often overlook the essential assumption of unattenuated property rights necessary to allow trading. If an individual's rights to a commodity are uncertain, ill-defined, or restricted by location or use, transfer and trade of the commodity may be prevented. The key point is that merely by creating a well-defined system of rights and then allowing a free market to come into play, an efficient allocation of water can be achieved just as surely as if the federal and state water agencies imposed high prices to their customers.

Another disincentive to economic management of water demand is the large proportion of California water supplies that are contracted on long-term fixed price, subsidized federal contracts. Water users fortunate enough to hold these contracts are now and in the future "under the demand curve" by dint of the subsidy, and need not react to increasing prices which affect other users. There are suggestions from some federal agencies that this system of windfall water allocation will not be repeated in the future.

Two consoling aspects of economic demand management make it a viable institution at this stage of the state's water development. Like growing old, economic demand management looks more attractive when compared to the alternative. Given that the future will be characterized by shifting and increasing demands for water with restricted supplies, the only alternative to economic demand management is a system of physical rationing or quotas. Given the complexity of California agriculture, even an enlightened rationing system cannot judge relative priorities and profitabilities of water between districts. Considerable inefficiencies and inequities are bound to result. The second consoling aspect of economic methods is that much of the water supply held in intransigent ownership rights need not be affected. For an efficient economic solution to result, only water at the margin need actually be traded or transferred. Thus, if only a small proportion of the water supply were subject to economic management, it would go a long way toward equalizing the shifting regional supplies and demands.

#### POLICY AND PROGRAM ALTERNATIVES FOR WATER DEVELOPMENT AND USE

Given the above background on the nature of economic demand for water and the potential costs for additional supply, we now explore the implications of several possible policy alternatives for water development and use in California. These alternatives may be described through the following scenarios:

(1) Voluntary reallocation of present water supplies. If forced to do so, how could future water usage in California best be adapted to existing supplies; assuming that any changes in current water allocations and patterns of usage could be accomplished in such a way that they are satisfactory to all parties involved? Also, what would be the value of incremental additions to supply?

(2) Institutional paralysis. Suppose that California's water institutions are unable to resolve issues of transferability of water and water rights between sectors of use, and unable to agree on programs for development of new water supplies. What are the future implications of such institutional rigidities for allocation and pricing of water?

(3) Development regardless of costs. If future "needs" for water are to be projected and met through large-scale development of new supplies regardless of the costs and the economic value of water, what are the consequences for water allocation and pricing in California?

Although many cases intermediate among these three extremes are conceivable, we shall consider only these three scenarios to keep the discussion manageable. Our objective is to provide some rough quantitative estimates of the economic differences between the three scenarios.

#### Framework for Analysis

The framework for analyzing these scenarios is a simple, two-sector aggregative model for water allocation and pricing for the entire state of California.<sup>18</sup> The model is designed to take into account the desirability of different pricing policies for the two major sectors of water usage in California: the urban sector, and the agricultural sector. Such an aggregative model necessarily assumes away regional differences in water availabilities, costs, and demands. However, California's water system is now interconnected

to a substantial degree, and significant water transfers can be accomplished physically. We believe that such a model is useful for rough calculations relevant to issues of water policy at the state level.

The model is based on the following major premises:

- (1) Economic demand for water in each sector, urban and agricultural, will be affected to some degree as the price for water is changed; as substantiated in the discussion above.
- (2) Water rights and water contracts are property rights, and may be transferred at a price acceptable to both buyer and seller; as recommended by the Governor's Commission to Review California Water Rights Law.
- (3) The California water system has substantial financial obligations, and pricing of water to the two sectors must raise sufficient total revenues to meet these obligations without increases in the current support from general taxation.
- (4) Total annual water output delivered to the two sectors cannot exceed given annual supply capacity. We do not examine the implications of uncertainty in supplies.
- (5) Where more than one allocation of supply is possible within the constraints set by (3) and (4), a "best" solution is chosen to maximize total net benefits for the two sectors, defined as the total excess of economic "willingness-to-pay" over costs.

All costs and values in the model are measured in 1977 dollars. A sketch of the details of the model is given in the Appendix.

Table 2 shows that aggregate applied water usage in California in 1972 was about 37 million acre feet (MAF), with 5 MAF allocated to urban usage and 32 MAF to agricultural usage. Although very little water is reused at present by the urban sector, applied water usage in agriculture includes reuse of about 25 percent of the net supply. To take into account this reuse potential within agriculture, we shall base our analysis on net water usage for 1972 of about 30.6 MAF, of which 5 MAF is urban and 25.6 MAF agricultural.<sup>19</sup> Assuming that existing additional supply approximately balances groundwater overdrafts plus reductions in Colorado River imports pursuant to the 1963 U.S. Supreme Court decision in *Arizona vs. California*, we shall take the base supply capacity limit for net water as 30.6 MAF per year.

We assume that the agricultural sector holds water or contract rights to the entire 1972 allocation of 25.6 MAF per year, ignoring the "supplemental" status of a portion of this water. In exchange for these rights, the agricultural sector makes a fixed annual payment toward the coverage of fixed costs, taken here as \$4 per acre foot for a total of \$102.4 million per year. Any purchases from agriculture of water under these rights must be at a price satisfactory to agriculture, and payments for these purchases become the exclusive property of agriculture. Payment must be made for both the original use of the water and the subsequent reuse. One institutional conception of this process would be a "water bank" that would purchase and then resell water to urban users at a price sufficient to meet outstanding financial obligations.<sup>20</sup>

Water demand relationships are specified to be consistent with the earlier discussion. For the urban sector, a wholesale price elasticity of -0.25 is assumed at a wholesale water price of \$80 and a quantity of 5 MAF.<sup>21</sup> For the agricultural sector, a price elasticity of approximately -0.42 is assumed at a marginal value (selling price) for applied water of \$25 per acre foot and an applied water quantity of 32 MAF.<sup>22</sup> Details of these demand relationships are given in the Appendix.

The variable cost for urban usage is set at \$42 per acre foot in the model, approximately the present cost to the Metropolitan Water District of Southern California for pumping Colorado River water at commercial power rates. The variable cost for agricultural usage is set at \$8 per acre foot, which is a regionally-weighted cost for groundwater pumpage in California.<sup>23</sup> The total level of financial costs to be met annually is set at \$292.4 million per year, which is consistent with the postulated base prices, variable costs, and water allocations.

We shall explore two possible future levels of demand, based on the projections for 1990 and 2020 in "Alternative Future II" as defined by the Department of Water Resources.<sup>24</sup> Although these projections now are considered to be toward the high side of what is likely to occur, they will serve to illustrate the range of possible future situations. For 1990, "Alternative Future II" specifies increases above 1972 levels of approximately 40 percent in urban water usage and about 15 percent in agricultural usage. For 2020, the increases are about 100 percent for urban usage and 25 percent for agricultural usage. Since the price assumptions underlying these projections have not been stated, we shall assume that they correspond to the base prices specified here of \$80 per acre foot for urban usage and \$25 per acre foot for agricultural usage. An increase in these prices would reduce the quantity of water demanded.

#### Results for Base Case

Results for the base year demand assumptions are given in Table 6. Water allocations and prices are at the levels postulated for this base case. However, additional information is provided by the marginal values of additional supply for urban and agricultural water. These values are the maximum one would be willing to pay for additional water delivered to the wholesale distribution point for the sector, assuming that all additional costs for the additional supply will be paid from water revenues. Actually there is one common marginal value of supply, and the unit variable costs for the sector are added to it to obtain a value for delivered water.

Note that even the urban marginal value of supply is well below almost all of the costs for new water supplies given in Table 1. Only the lower-cost groundwater sources fall below this level, and as discussed previously the cost of conveyance should be added to these costs to provide a delivered cost comparable to the urban marginal value of supply. Given the situation of the base year data, addition of available new sources of supply seems economically unjustifiable.

TABLE 6  
Base Year Water Allocation and Pricing Results

Results	dollars per acre foot	million acre feet
Urban water consumption (net)		5.00
Agricultural water consumption (net)		25.60
Urban water price (applied)	80.00	
Agricultural water price (applied)	25.00	
Urban marginal value of supply	63.25	
Agricultural marginal value of supply	29.25	

Results for Policy Scenarios

We now turn to the analysis of the three policy scenarios under the 1990 and 2020 demand specifications. Recall that the *Voluntary reallocation* scenario assumes no additional water supplies but that voluntary sale of water is possible; the *Institutional paralysis* case assumes that variation from the base year allocations cannot be accomplished, and the *Development regardless* scenario assumes new development is pursued regardless of cost. More specifically, the last case augments water supply capacity by all of the new surface water development and groundwater storage discussed previously: 3.3 MAF per year of surface water at an average development cost of \$160 per acre foot, and 0.25 MAF per year of groundwater at an average cost of \$60 per acre foot. The effect of this development is to add 3.55 MAF per year to supply capacity, and \$543 million per year to the financial costs to be met by the system.

Water allocation and pricing results for the three scenarios in 1990 and 2020 are given in Tables 7 and 8. In the *Voluntary reallocation* scenario, water is transferred from the agricultural to the urban sector as demand relationships shift over time. In the 2020 case, agriculture sells about 4.7 net MAF to the urban sector. This is still only about 18 percent of the initial allocation of water to agriculture, so even without additional water supplies, agriculture would remain a major economic activity in California. For this sale, agriculture would receive \$47.29 per acre foot of net water, based on reuse of 25 percent and an excess of price over pumping costs of \$37.83 per applied acre foot. From the marginal values of supply given for this case in Tables 7 and 8, very few of the additional sources of supply included in Table 1 would seem economically justifiable even under 2020 conditions--only the lower-cost groundwater storage schemes, and possibly large-scale municipal wastewater reuse depending on the conveyance costs for the water.

In the *Institutional paralysis* case, the price of water for urban usage is driven to high levels by the rigid quantity restriction; in 2020 it is three times the base year level. This does not necessarily mean that water rates would reach this level. Rather, rationing and growth restrictions would be likely to result in a high effective price even if actual water rates were held down. Here the urban sector could justify substantial expenditure for additional supply based upon the marginal values given. The agricultural sector, however, could not.

In the *Development regardless* scenario, it seems almost paradoxical that the urban sector in 1990 receives a reduction in water allocation despite the increased overall supply. The reason for this is that urban water prices must be raised substantially to pay for the costs of the expensive additional supply. The price to agriculture, which has less revenue-raising capability, is held down to provide full utilization of capacity. The additional supply capacity leads to lower marginal values for additional supply than in the *Voluntary reallocation* case.

Comparison of Policy Scenarios

To provide a quantitative assessment of the three policy scenarios, total economic benefits have been calculated for each. Given that the marginal value of additional supply was found to be relatively low in comparison to the cost of development, it should not be surprising that the *Voluntary reallocation* case has the highest level of net economic benefits. However, if the losses from adopting another scenario are small, one might justify its adoption on the basis of other considerations not included in the analysis here.



TABLE 7

Water Allocation and Pricing Results for Three Scenarios, 1990

Results	Voluntary reallocation	Institutional paralysis	Development regardless
Urban water consumption (net) (million acre feet)	7.01	5.00	4.93
Agricultural water consumption (net) (million acre feet)	23.59	25.60	29.22
Urban water price (applied) (dollars per acre foot)	79.47	171.43	174.71
Agricultural water price (applied) (dollars per acre foot)	36.93	32.83	25.44
Urban marginal value of supply (dollars per acre foot)	78.18	171.43	59.07
Agricultural marginal value of supply (dollars per acre foot)	44.18	39.03	25.07

TABLE 8

Water Allocation and Pricing Results for Three Scenarios, 2020

Results	Voluntary reallocation	Institutional paralysis	Development regardless
Urban water consumption (net) (million acre feet)	9.71	5.00	8.50
Agricultural water consumption (net) (million acre feet)	20.89	25.60	25.65
Urban water price (applied) (dollars per acre foot)	89.29	240.00	128.03
Agricultural water price (applied) (dollars per acre foot)	45.83	37.00	36.90
Urban marginal value of supply (dollars per acre foot)	89.29	240.00	78.11
Agricultural marginal value of supply (dollars per acre foot)	55.29	44.25	44.11

CONCLUSIONS

Estimates of the net economic losses entailed by adopting one of the other policy scenarios in place of *Voluntary reallocation* are given in Table 9. These losses are substantial, measuring in the hundreds of millions of dollars annually. In the *Development regardless* alternative, the loss calculation includes the additional cost of \$543 million per year for the additional supply-note that in 1990 there is a loss even before including this cost.

TABLE 9

Estimates of Net Economic Loss versus  
"Voluntary Reallocation" Scenario

Year	Relative net economic loss (million dollars per year)	
	Institutional paralysis	Development regardless
1990	100.3	557.0
2020	380.9	425.1

It is likely that the loss estimates for the *Institutional paralysis* case understate the true amount. First, these calculations have been made under the assumption that water would be allocated to the most valuable economic uses within each sector. It is expected that misallocations due to rationing and growth restrictions in the *Institutional paralysis* case would yield even greater losses. Second, the model assumes that base year allocations are efficient. It seems plausible that full implementation of a *Voluntary reallocation* scenario would yield improvements in efficiency even under the base conditions. These improvements would widen the gap between these two scenarios even further.

One also may make inferences about several considerations not explicitly included in the analysis here. Conservation measures would tend to reduce demand and shift the 2020 situation in the direction of those for 1990 or 1972--such a shift would reduce the value of additional capacity. Lowering the growth projections would have the same effect. Addition of other supplies not included here, such as municipal wastewater reuse or the Peripheral Canal, would also lower the value of additional capacity. Any, or all, of these measures would tend to make the gap between the *Voluntary reallocation* and the *Development regardless* scenarios even larger.

This paper has attempted to examine the current allocation institutions for water in California from a historical and economic perspective. Three broad results emerge from the analysis. First, that institutions governing economic resources should be responsive to changing economic pressures; and that the increasing scarcity and cost of additional water supplies will push the California water sector into a system of institutional as well as physical adaptation.

Second, a move toward pricing institutions to allocate water is advantageous. Prices are very efficient conveyors of information on the relative scarcity of resources. The move toward price allocation of natural resources has strong precedents in other areas of scarcity.

Third, that preliminary investigations of the effect of price systems both within and between sectors do not lead to drastic shifts in allocation; but the cost of institutional paralysis is very high.

Policy recommendations based on these findings can be summarized by stating that institutions should be modified to allow increased use of market forces to allocate water. Specifically this would involve: greater certainty of ownership rights, as opposed to use rights, for water under existing contracts; adjudication of groundwater resources; institutions to facilitate resale of water under existing contracts; an institution to ensure that fixed cost obligations of water districts will be met regardless of water transfers or sales.

In conclusion, it seems paradoxical to us that advocating a trend toward market pricing institutions for allocation of California's water resources should be regarded as "radical" by many interest groups who are self-styled conservatives. Water is not "different."

FOOTNOTES AND REFERENCES

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8. See Giannelli and Eiland, 1977. The lowest cost share mentioned in that report is 8 percent for strawberries. William R. Giannelli and Robert G. Eiland, Ability of Agriculture to Pay for Water, prepared for the Eastern and Western Water Districts of Riverside County and the Municipal Water District of Orange County, June 1977.
9. R.E. Howitt, W.D. Watson, and R.M. Adams, A Reevaluation of Price Elasticities for Irrigation Water (forthcoming), Department of Agricultural Economics, University of California, Davis.
10. U.S. Bureau of the Census, 1972 Census of Manufacturers, Water Use in Manufacturing in 1973, Table 2B, USGS Circular 676 Table 8. Note that the figures for brackish and saline water refer to withdrawals of water for these uses; most of these waters are returned to the source after use.
11. The main explanation for these differences lies in the methodology used to compile the estimates of manufacturing consumption. The DWR estimates are based on two surveys conducted in 1960 and 1972 involving a questionnaire mailed to every manufacturing establishment. About 19 percent of the firms responded to the questionnaires and their responses were "blown up" to the whole manufacturing sector by a procedure which almost certainly introduced substantial inaccuracies. By contract, the U.S. Census Bureau aims for a complete survey of every manufacturing establishment using 20 million gallons (MG) of water or more per year. Obviously, the Census figures underestimate water consumption because they exclude small water-using establishments. However, there is evidence from both the Census Bureau and the DWR survey that these small water-using establishments account for only three or four percent of aggregate water intake in the manufacturing sector. This implies that, as a first approximation, the Census estimates of water consumption should be multiplied by  $1.04 = (0.96)^{-1}$  to obtain an estimate of consumption by the entire manufacturing sector. Even with this correction, the discrepancies between the Census and DWR estimates of manufacturing water use are substantial. One cannot escape the conclusion that the DWR estimates are exaggerated by the data extrapolation procedures.
12. The recirculation rate is the ratio of gross water used (i.e., the amount of water which would have been required if no water had been recirculated or reused) to total intake water. The DWR data give a quite different picture: according to Bulletin No. 124-2, the recirculation rate increased from about two times in 1957-1959 to about 6.7 times in 1970 for the sample of establishments responding to the DWR survey. Water Use by Manufacturing Industries in California, 1957-1959, Bulletin No. 124, California Department of Water Resources, April 1964.
13. For example, Fourt (1958) obtained an elasticity of -0.4, Renshaw (1958) obtained an elasticity of -0.45, Turnovsky (1969) obtained an elasticity of -0.3, and Lynne and Gibbs obtained an elasticity of -0.37.  
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19. The California Water Plan: Outlook in 1974, Bulletin No. 160-74, Department of Water Resources (Sacramento: 1974).
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21. Based on a margin between retail and wholesale prices of \$80 per acre foot, a retail price elasticity of -0.3 for household usage, a retail price elasticity of -1.0 for commercial and industrial usage, and 70 percent of urban usage by households as given in Water Conservation in California, Bulletin No. 198, Department of Water Resources (Sacramento: 1976).
22. Price elasticity from R.E. Howitt, W.D. Watson, and R.M. Adams, "A Reevaluation of Price Elasticities for Irrigation Water," Department of Agricultural Economics, University of California, Davis, forthcoming, as adjusted for all crops assuming zero price elasticity for nonincluded perennials and orchard crops; marginal value from Governor's Commission to Review California Water Rights Law: Final Report (Sacramento: 1978) p. 56.
23. H.J. Vaux, Jr., unpublished data (Riverside: University of California, 1978).
24. The California Water Plan: Outlook in 1974, Bulletin No. 160-74, Department of Water Resources (Sacramento: 1974).
25. If  $\bar{Q}_2 = 0$  and  $\tau_1 = \tau_2 = 0$ , the model (1') - (4') is identical to the one analyzed in D. Erlenkotter, Should California Agriculture Receive Preferential Water Rates, Working Paper No. 285 (revised), (UCLA: Western Management Science Institute, November 1978).
26. Ibid.

Some of the group discussion dealt with the nature of the resistance to open-market transfer of water rights. Some of the participants expressed the viewpoint that some legal and institutional barriers may exist, but the chief problem is one of emotions and attitudes. "They could sell it now if they wanted to, but they don't." Others pointed out that there are specific impediments--for example, districts at present can sell only "surplus" water and fear that they may lose their rights to even that water if they transfer it. The question of possible "corrosion" of property rights in water is crucial. The economists' viewpoint is that if farmers are given firm property rights to their water and are offered a profitable price for it, their resistant attitude will change quickly. One suggestion is that the term "selling" water rights should be used instead of "transferring," since it is both more accurate and probably more acceptable. A complicating factor is that, at present, neighboring water users who may be affected by a sale may not have any recourse; but if their rights were quantified and firm, they would.

Other questions concerned the sensitivity of the estimates of economic loss to changes in parameters in the analysis. The authors reported that they have tried various systems for calculating them, and get generally comparable results from each. Some parameters don't make much difference for policy-making purposes; for instance, changes in the price elasticity of demand for urban water use does not greatly alter the results of the analysis. Many of the calculations are based on Department of Water Resources estimates, some of which are changing with time. Also needed is more information on the kinds of informal or formal exchanges of water that have actually taken place in recent years.

Is the establishment of rights and transfers for groundwater and instream uses more complicated than for surface water? The "common pool" problem comes up here. Since oil and gas owners and groundwater users in other states make collective, group arrangements, there seems to be no fundamental reason why it can't be done here. In regard to "third party" effects--some should be accepted, as in other sectors, to achieve efficiency. It's a matter of balancing efficiency and equity.

Where water resources are partially subsidized by the public the granting of firm ownership and transfer rights would probably confer substantial windfall gains on some groups. Is this inequity inevitable? Some windfall gains are necessary to provide an incentive for the present allocation system to change. If these incentives ensure that some parts of the state are better off and no one is worse off due to more efficient use of water, why not let some parties use windfall gains, as long as they are not excessive.

APPENDIX

The two-sector water allocation and pricing model is formulated as follows:

$$\text{Maximize } \left[ \begin{array}{l} \text{Total excess of willingness-to-pay} \\ \text{over marginal cost, or sum of} \\ \text{consumers' plus producers' surpluses,} \\ \text{for urban and agricultural sectors} \end{array} \right]$$

subject to the following constraints:

$$[\text{Total annual output}] \leq [\text{Capacity}]$$

$$[\text{Net operating revenues}] \geq [\text{Annual fixed costs}].$$

In mathematical notation, this becomes

$$\begin{aligned} \text{Maximize } & \sum_{j=1}^2 \int_0^{Q_j^A} [p_j(Q_j) - c_j] dQ_j \\ Q_j^A & \geq 0 \quad j=1, 2 \\ Q_j^N & \geq 0 \end{aligned}$$

subject to

$$\sum_{j=1}^2 Q_j^N \leq \bar{Q}$$

$$-[p_1(Q_1^A) - c_1]Q_1^A - [p_2(Q_2^A) - c_2](Q_2^A - (1 + r_2)\bar{Q}_2) \leq -[F - \epsilon_2\bar{Q}_2]$$

$$Q_j^A = (1 + r_j)Q_j^N$$

where

$Q_j^A$  is the annual applied use of water by sector  $j$  ( $j = 1$  for urban,  $j = 2$  for agricultural),

$p_j(Q_j^A)$  is the price per unit corresponding to a total demand for applied water of  $Q_j^A$  for sector  $j$ ,

$c_j$  is the (constant) marginal cost per unit of water delivered to sector  $j$ ,

$Q_j^N$  is the net water demand (consumptive use) for sector  $j$ ,

$\bar{Q}$  is the fixed capacity for total annual availability of water,

$\bar{Q}_2$  is the annual net amount of water controlled by the agricultural sector through contracts or water rights,

$F$  is the total annual fixed cost that must be met through operating revenues,

$\epsilon_2$  is the fixed payment per unit of the allocation  $\bar{Q}_2$  that must be paid by the agricultural sector as a consequence of contract or water rights obligations,

$r_j$  is the reuse fraction for sector  $j$  that relates net water use to applied water use.<sup>25</sup>

(1) To interpret constraint (3'), note that the term on the right-hand side gives the net fixed charge amount that must be paid after deducting contractual payments from the agricultural sector. On the left-hand side, the first term gives net revenues from the urban sector after deduction of variable costs. If

(2)  $Q_2^A < (1 + r_2)\bar{Q}_2$ , the second term requires payment for purchases of water in the amount  $(1 + r_2)\bar{Q}_2 - Q_2^A$  from the agricultural sector. If  $Q_2^A > (1 + r_2)\bar{Q}_2$ , this

(3) term gives the net proceeds for sales of water in the amount  $Q_2^A - (1 + r_2)\bar{Q}_2$  to the agricultural sector. Payment for transfers to and from the agricultural sector is based on the net price (marginal value) for applied water

(1')  $p_2(Q_2^A) - c_2 \geq 0$  since at this level the marginal agricultural user is indifferent between using or selling water. Note that constraint (3') provides for payment to both the original user of agricultural water and the subsequent reuser.

(2') From the solution to the model (1') - (4'), one obtains optimal values for the water quantities  $Q_j^*$  and the prices  $p_j(Q_j^*)$ . One also obtains the marginal value,  $v^*$ , for adding another unit of capacity to  $\bar{Q}$  in constraint (2'), and the marginal cost,  $\lambda^*$ , for adding another dollar to the fixed cost  $F$  in constraint (3'). From these amounts one may calculate an adjusted marginal value of additional supply under the requirement that additional costs for the supply are paid from revenues and hence enter into constraint (3').<sup>26</sup> This adjusted marginal value of supply, which is the maximum one would be willing to pay for an additional unit of capacity if financed through water revenues, is calculated as  $v^*/(1 + \lambda^*)$ . The marginal value of supply reported here for water delivered to sector  $j$  is then  $c_j + v^*/(1 + \lambda^*)$ .

For the numerical calculations performed here, linear demand functions  $p_j(Q_j^A)$  are postulated:

$$p_j(Q_j^A) = a_j - b_j Q_j^A \quad \text{for } j = 1, 2$$

where  $a_j$  and  $b_j$  are chosen to correspond to empirical estimates of demand elasticities. Values used for these parameters are:

j	a <sub>j</sub>	b <sub>j</sub>		
		Base	1990	2020
1	400	64.000	45.714	32.000
2	85	1.875	1.630	1.500

As discussed in the text, these parameters are chosen to yield a price elasticity of demand  $(p_j/Q_j)dp_j/dQ_j$  for sector 1 of -0.25 at a wholesale water price of \$80 per acre-foot, and for sector 2 of about -0.42 at a water price of \$25 per acre-foot.

Values used for other parameters are  $c_1 = \$42$  per acre foot,  $c_2 = \$8$  per acre foot,  $\bar{Q}_2 = 25.6$  MAF/year,  $f_2 = \$4$  per acre-foot,  $r_1 = 0$ , and  $r_2 = 0.25$ .

For the *Voluntary reallocation* and *Institutional paralysis* scenarios,  $\bar{Q} = 30.6$  MAF/year and  $F = \$292.4$  million/year, while for the *Development regardless* scenario,  $\bar{Q} = 34.15$  MAF/year and  $F = \$835.4$  million/year.