ECONOMIC IMPACTS OF ALTERNATIVE WATER ALLOCATION INSTITUTIONS IN THE COLORADO RIVER BASIN

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FOREWORD

The contents of this report were developed under a grant from the Department of the Interior, U.S. Geological Survey. However, those contents do not represent the policy of that agency and the reader should not assume endorsement by the Federal Government.

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The research was aided by the cooperation of numerous people in local, state and federal water agencies who assisted us by providing access to data and experience on the supply and demand for Colorado River water. We particularly wish to acknowledge the assistance of colleagues in the Department of Agricultural Economics, Colorado State University. Garth Taylor and Laurie Walters aided in preparing data and models used in deriving estimates for agricultural and municipal demand relationships. Dr. Edward Sparling helped in formulation of the mathematical models.

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ABSTRACT

Colorado River water is the dominant water supply for much of the southwestern United States, satisfying agricultural, municipal, and industrial needs. Basin water is now fully utilized, and new demands, particularly in Arizona and rapidly growing southern California, will cause increasing pressure to reallocate basin water. Water transfers would require foregoing some existing uses and would be possible only with significant institutional changes in the set of compacts, state laws, and court decisions which together control allocation of Colorado River water.

Instream flows are used at many basin locations for hydropower production. Water quality improvements which reduce salinity concentrations increase crop yields and lifetimes of household appliances. These nonconsumptive uses of Colorado River water physically interact with consumptive uses and are of similar economic significance.

The objective of this work is to evaluate policies for increasing beneficial use of basin water resources. This is achieved by estimating consumptive and nonconsumptive use benefits using a nonlinear economic optimization model. Up to fourteen water demand sectors are linked with river flows to find allocations maximizing net economic surplus under alternative institutions. The work extends previous efforts on Colorado River allocation by including all major use sectors in an integrated economic-hydrologic optimization model. For the first time, alternative water allocation institutions and economic values are formally considered in a full Colorado River basin model.

Solutions are found under priorities governing present allocation, and under increased intra- and interstate trade between existing consumptive and nonconsumptive users. Model solutions are presented using estimates of present and future economic demands under two levels of basin water flow. The first flow level is equivalent to estimates of the long-term mean, while the second simulates serious drought, or a climate change induced reduction in mean flows.

Present consumptive uses are almost satisfied in full with the first flow level. Significant shortfalls occur under other conditions, and within-state water transfers are found to be particularly effective for increasing net consumptive use benefits. It is concluded that continued emphasis on facilitating within-state transfers will have the greatest impact in achieving economic efficiency in basin water use.

EXECUTIVE SUMMARY

The Colorado River is the dominant river system in the southwestern United States, providing water for agriculture, households, hydropower production, industry, recreation, and wildlife. The river basin includes portions of the states of Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California. Much of the native flow is exported from the drainage basin; over 90% of use by California, the largest single user of Colorado River water, is outside the basin. Mexico receives by treaty about 10% of the average flow, utilizing basin water for irrigation and municipal use in the Mexicali Valley. The river mouth at the Gulf of California is now dry except during unusual high flow events.

Growing demands for Colorado River water from within and outside the basin are stimulating searches for new supplies and consideration of changes to the institutions which have dominated river allocation for the past century. Southern California urban areas, already the largest municipal users of basin water, are projected to grow by up to 4 million people by the year 2010, while Arizona has recently begun significant withdrawals for the Central Arizona Project. Accelerated development of upper basin energy resources remains a distinct possibility, with corresponding implications for upper basin water demand. Development of water resources for municipal and agricultural uses in the upper basin continues, leading to concern that provision of adequate supplies may be possible only by developing new sources outside the Colorado River basin.

Scarcity of basin water for consumptive uses is not the only issue: other uses of basin water resources are of similar economic significance. Instream flows are used at many basin locations for hydropower production. Water quality considerations, reflected in dissolved solids (salinity) concentrations adversely affect crop yields and lifetimes of household appliances (Miller, Weatherford, and Thorson, 1986). These nonconsumptive uses of Colorado River water physically interact with consumptive uses and are thus impacted by water allocation decisions in the basin.

The objective of this work, suggested by the supply and demand changes noted above, is to evaluate policies for increasing net economic returns to basin water resources. Generally, any policies which result in water transfers from lower valued to higher valued uses will increase beneficial use. Water markets are frequently advocated (Anderson, 1983) as a means of achieving more economically efficient allocations. Water markets may include temporary leasing during shortages and permanent water right transfers. Specific market driven proposals for interbasin transfer of Colorado River water have been made (Gross, 1985, and Martz, 1990).

In this study, allocations that maximize estimated economic benefit of both consumptive and nonconsumptive water use are derived using a nonlinear economic optimization model. Up to fourteen water demand sectors are linked with river flows to find allocations maximizing net economic surplus under alternative institutions. The work extends previous efforts on economic allocation of Colorado River water (Oamek, 1990; Lee, 1989; and Brown, Harding, and Lord, 1988) by including all major use sectors in an integrated economic-hydrologic optimization model. For the first time, alternative water allocation institutions and economic values are formally considered in a full Colorado River basin model.

Solutions are found under the priorities governing present allocation, and under increased within-state and interstate trade between existing consumptive and nonconsumptive users. Model solutions are presented using estimates of present and future economic demands under two levels of basin water flow. The first flow level is equivalent to estimates of the long-term mean, while the second simulates serious drought, or a climate change induced reduction in mean flows.

Scope of Analysis and Model Assumptions

This research focuses on direct economic efficiency impacts of alternative water allocation institutions, one of many possible objectives in management of basin water resources (National Academy of Sciences, 1968). A broad national accounting stance is used throughout the analysis, so that policy impacts are assessed from the perspective of all water users, rather than from a single state. Secondary economic impacts (pecuniary externalities) are not treated and net benefits or costs from such impacts are thus assumed to be zero in the formal analysis.

A nonlinear optimization model was formulated to estimate impacts of alternative institutional scenarios, river flows, and economic demand levels. Termed the Colorado River Institutional Model (CRIM), it links river flows, salinity concentrations, and demand sectors across river locations. Consumptive use benefits, hydropower benefits, and costs and benefits of salinity production are incorporated as integral model components. CRIM is formulated as a two-commodity flow optimization problem with the objective of maximization of net economic surplus (defined over selected economic sectors), subject to physical and institutional constraints. Economic surplus is a function of levels of the two commodities, water quantity and salinity at the economic demand sectors. The mathematical programming model is constructed using the GAMS higher level language (Brooke, Kendrick, and Meeraus, 1988) and is solved using the MINOS optimization program developed by Murtagh and Sanders (1980). The basin is modeled as a single mainstem with all demand and supply sectors occurring as simple tributaries or diversions. Above the Colorado-Green River confluence the Green River is chosen as the mainstem.

A full basin water budget underlies this research. All sources and consumptive uses of basin water are included in the analysis. Most major users of basin water resources are explicitly included as economic actors; exceptions are noted below. CRIM is a static model, with specific long-term average flow levels used to represent annual flows. This approach implicitly assumes that excess flows in individual years are captured by basin reservoirs and remain available for use in subsequent years.

Economic Valuation

Water values are known to vary widely by use, location, and over time. Standard techniques presented in Young and Gray (1972) are used to estimate economic benefits from specific uses of basin water resources. Residual imputation using linear programming models, and avoided cost are the primary techniques for valuing water use in agriculture and energy production, respectively. Municipal benefits are developed from econometric estimates of household water demand functions, and utilize residual imputation to account for conveyance and treatment costs for Colorado River water.

It is implicitly assumed throughout the analysis that valuation of water use at the margin of use is appropriate. Noneconomists have expressed concern that transfers of agricultural water may result in retirement of a broad class of crops, and, by implication, sacrifice average economic values of water. In contrast, the use of linear programming techniques here to value water use in agriculture assumes that marginal values alone reflect the opportunity costs of transfers from agricultural uses. Approximations to marginal values also are developed for other use sectors.

A long run perspective is generally taken. Costs of production in agriculture include all capital costs; resulting derived water demands are true long run estimates. Valuation of hydropower assumes that capital costs of alternative generation sources are sunk costs. This is most valid at present with excess generating capacity in the western United States, but may significantly underestimate avoided costs in the future. Capital costs of refurbishing hydropower plants are also not considered. Water demand for energy production from fossil fuels is derived using the capital costs of water saving technologies. Capital costs of municipal conveyance and treatment facilities are not considered. These costs have already been incurred; only recurring and operations and maintenance costs of water treatment and delivery are included in municipal water demand estimates.

Economic benefit measures of salinity abatement are highly controversial. Economic impacts of salinity changes were based on studies performed in the 1970's, updated to 1988 price levels.

The economic demand for use of basin water resources is estimated for years 1990, 2010, and 2030. Impacts of institutional change under both present and future demands are considered.

Economic Sectors in the Model

Economic surplus measures are explicitly developed for the Grand Valley (Colorado), Imperial Valley (California), southern California municipalities, cooling water for fossil fuel energy resources (coal fired electric generation, coal gasification, and oil shale) in northwest Colorado, and hydroelectric generation at Glen Canyon, Hoover, Davis, and Parker Dams. The level of all other basin water demands and requests use data developed by the USBR (1986b) for use in its Colorado River Simulation Model, or CRSM (USBR, 1986a).

The estimated derived demand functions for the Grand Valley and Imperial Valley are extrapolated to additional major agricultural sectors in the upper and lower basins, respectively. These agricultural users together account for 7.8 maf of the estimated total (United States) Colorado River basin consumptive use (not including reservoir evaporation) of 11.4 maf in 1990. The high level of aggregation in estimation of agricultural water demands is troubling, but resource and time constraints precluded more detailed study.

Allocation of basin water to economic demand sectors is estimated by CRIM through maximizing economic surplus of the included demand sectors under the postulated institutional constraints. Under certain institutional scenarios, economic demands are met by assumption, up to some maximum consumptive use level. Consumptive use requests not included as economic demand sectors (3.6 maf in 1990) are met according to existing institutional priorities. The resulting allocations are then fixed as alternative institutional scenarios are considered. Nonconsumptive uses other than hydropower production and salinity reduction are not formally considered in the analysis.

The profit and consumer surplus functions used in the objective function are expressed as net benefits (and salinity costs) from withdrawals at the river. Conveyance costs are thus only implicit in the model; they are not the focus of this study. All conveyance costs are netted out in the profit and consumer surplus function definitions. Use of withdrawals simplifies incorporation of instream hydropower benefits. Specific constraints imposed on specific scenarios to simulate the institutional environment are discussed below.

Institutional Scenarios

The focus of this study is the investigation of impacts of alternative institutions on Colorado River water users from a national and regional perspective. Of particular interest are institutions allowing water transfers based on economic values in alternative uses. Estimated impacts of several alternative institutional scenarios are presented. The first scenario simulates allocation of Colorado River water under existing interstate and within-state priorities. The second allows within-state transfers based on water values in consumptive uses. Interstate water transfers based on consumptive use values alone are then introduced. Scenarios including both consumptive and nonconsumptive use values are then presented. A scenario including all identified economic values and allowing unrestricted transfers is the most comprehensive institutional scenario considered in this research.

Analytic Approach And Results

Hydrologic Modeling

Ten-year average water flow levels are used as the basin water supply. Use of such a long-term average is appropriate given basin reservoir storage of approximately four times average annual flows. Two flow levels are considered. The first is constructed from historical flow records for the period 1906-1983; the average annual flow of 13.0 maf is below the historic mean, but is very near long-term mean flow levels reported by Stockton (1975). (The long-term flow estimates were reconstructed from tree-rings; the record reaches back to the year 1560.) Use of the long-term mean flow levels defines a "base" model for this research.

The second flow level simulates drought under the long-term flow estimates and is used to estimate the performance of alternative water allocation institutions under significant stress. An average annual flow of 11.5 maf is used to define a "drought" model. An alternative interpretation of the lower flow level is a climate change-induced reduction in mean flows (see, for example, Gleick, 1989).

For the flow scenarios specified above, basin reservoirs are expected to be drawn down to meet shortfalls in filling requests for basin water. Simulations of basin reservoir operations (USBR, 1986c) are used to estimate the level of additional supplies from storage under alternative model definitions. Annual releases from storage are 0.2 maf and 0.8 maf for the "base" and "drought" models, respectively. Because reservoir surface area decreases with releases from storage, reservoir evaporation is given as a function of flow levels.

The model formulation is static and thus unable to include impacts of short-term events, or lags within the hydrologic system. For example, impacts of changes in salinity loading are known to be significantly lagged: reductions in upper basin salinity loading may not result in reduced lower basin salinity levels for several years. This lag is incorporated in CRIM by discounting the value of salinity damages experienced by lower basin water users (Gardner and Young, 1988).

A number of other sensitivity tests to key parameters, including alternative water supplies and economic benefit measures, are performed. These results are not reported in this summary.

Base Model Results

Under base model flows of 13.0 maf/year and 1990 demand levels, most requests for basin water can be fully satisfied. The small basin shortfall of 260 kaf found with this flow level is borne by southern California municipal users served by the Metropolitan Water District (MWD), the junior rightholders in the lower basin. With present upper basin request levels, upper basin consumptive use is not constrained by the Lee's Ferry delivery requirement of 8.25 maf per year under base model flows. Significant development above present levels, however, would inevitably lead to a greater likelihood of shortfalls in dry periods. Other basin water users are well protected during dry periods, and might not experience any of the opportunity costs of water shortages experienced by more junior users.

Impacts of Within-State Water Transfers. - Removing barriers to water marketing within California would likely result in significant transfers between southern California municipal users and California agricultural water rights holders. Any reallocation which either elevated MWD's junior rights, or reduced existing consumptive uses by more senior rights holders would be a gain for southern California municipal users. Model results indicate that with present demand these municipal users would benefit in dry periods from water transfers up to the Colorado River Aqueduct capacity if marginal costs (i.e., foregone benefits in alternative uses) are less than $300/af. Imperial Valley irrigators could benefit from such transactions at prices as low as $20/af. For comparison, in a study covering water demand throughout California (using methods similar to those employed here), Vaux and Howitt (1984) reported marginal values of $210/af in southern California municipal uses and $45/af in Imperial Valley agriculture in a 1980 scenario (values adjusted to 1989 constant dollars using the GNP deflator). For 1995 they estimated values of $360/af and $60/af, respectively. Their study predicted very large transfers from the Imperial Valley (over 1 maf) in both scenarios, accounting for much of the difference in marginal values.

The total value to southern California municipal users of eliminating the 260 kaf shortfall found under existing priorities with the base model definition is estimated at $100 million annually. If distributed over the estimated MWD service area population of 15 million in 1990, annual benefits (not including costs paid to Imperial Valley irrigators, or salinity damages) are about $7 per capita. Estimated annual benefits rise to $800 million in year 2030 for eliminating a 800 kaf/year shortfall, given a projected population increase to 23 million. Per capita total benefits are then $35 annually. If acquisition costs are $130/af (the cost to MWD in the recent transfer agreement with the Imperial Irrigation District, or IID), then the net benefit (still excluding salinity damages) to southern California municipal water users is $30 per capita per year.

Impacts on salinity levels and hydropower generation from transfers between California users of Colorado River water would be small. The dominant salinity impact would be increased damages to southern California municipal water users from higher salinity levels. In principle, this impact would be accounted for in decisions by MWD on importing Colorado River water.

Impacts of Interstate Water Transfers. - Interstate water transfers would doubtlessly require significant changes in the institutional framework governing Colorado River water allocation. Such change could be stimulated by persuasive evidence that significant economic benefits could be achieved by allowing interstate transfers. Model runs with present demand levels do not show significant gains if only consumptive use values are considered, given the existing possibility for within-state transfers. In this scenario upper basin use declines by 150 kaf over the full request level, with the reductions distributed across agricultural areas with total present use levels of 2300 kaf. Upper and lower basin marginal water values are $18 and $19/af, respectively.

If nonconsumptive use values are included, however, significant economic benefits are possible with upper to lower basin transfers, particularly from salt producing agricultural regions. Upper basin use would be substantially reduced from present use levels because of downstream benefits in increased hydropower production and salinity reduction. The model predicts transfers would be 760 kaf or 33% of included agricultural demands, the maximum allowed transfer. (Upper basin agricultural demand functions are not defined below 67% of existing use levels in this analysis; transfers resulting in greater reductions in upper basin use are thus excluded by assumption.) Estimated upper and lower basin marginal water values are $96 and $52/af, respectively. The marginal value estimates include marginal benefits of consumptive use, hydropower production, and salinity reduction by dilution. The estimated marginal value of reduced upper basin salinity loading is $56/ton.

Concluding Remarks on Base Case. - The maximum economic benefit achievable through water transfers of Colorado River basin water, relative to allocations by existing priorities, is estimated $185/af with a water transfer of nearly 800 kaf from the upper basin. Mexican users would also benefit from salinity reductions and possible increased deliveries. For comparison, allowing only intrastate transfers between MWD and the Imperial Valley gives average net gains over existing allocation priorities estimated at $65/af for a 260 kaf transfer. There would be minimal impacts to hydropower generation and Mexican deliveries.

Drought Model Results

Drought under the long-term flow estimates substantially increases the shortfall in meeting requests for consumptive use of basin water. In contrast to the higher average flow level of 13.0 maf, upper basin shortfalls caused by the Lee's Ferry delivery requirement occur and are substantial (1.1 maf). Under existing priorities, lower basin shortfalls continue to impact only MWD water users, but increase to 0.4 maf. Impacts of institutional innovation are shown to be somewhat different than estimated under the higher flow level.

Allowing within-state water transfers is again shown to result in substantial economic benefits, particularly in California. Interstate transfers based only on consumptive use values would move water use from the lower to upper basins; while initially surprising, this result is the consequence of the large marginal value for upper basin irrigation water assumed at significant reductions in supply relative to lower basin agricultural water values near full supply levels.

If nonconsumptive use values are considered however, the lower to upper basin transfers suggested by the model results clearly do not yield improved economic benefits.

Transfers based on all nonconsumptive and consumptive use values would again result in transfers from upper to lower basins, thus increasing the total upper basin shortfall.

Concluding Remarks

Model results provide numerical estimates of economic efficiency impacts of institutional change, and lead to several fundamental policy conclusions. First, water transfers from agriculture to MWD water users would result in substantial economic benefits, further confirming the well-known difference in marginal water values in agricultural and municipal uses. Second, there is very limited motivation for interstate water transfers based on consumptive use values alone. (Upper to lower basin transfers, were they to actually occur, would likely take place directly between agricultural and municipal users.) Because differences in marginal economic values of consumptive use are modest between upper and lower basin agricultural users, any gains from trade would be equally modest. Predicted economic benefits of upper to lower basin transfers become significant, however, when nonconsumptive use values are considered: reductions of salinity concentrations and hence damages, and increased hydropower production are economically important. (Lower to upper water basin water right transfers are predicted to be advantageous under extreme drought when only consumptive use values are considered. Lower to upper basin transfers are always economically inefficient when all values are considered, however, and would result in a reduction in net benefits from use of basin water resources.)

While market based interstate transfers are possible, this research suggests that they are unlikely. This conclusion follows because additional benefits from interstate consumptive use markets, beyond those possible employing only within-state market, are relatively small. If interstate transfers were to occur, they would likely be the result of constraints on lower basin within-state transfers, particularly in California. Ironically, if all water use values across all basin water users are considered, interstate transfers resulting from constraints on

water transfers within lower basin states would be economically efficient.

CHAPTER 1

INTRODUCTION

The Colorado River is the dominant river system in the southwestern United States, providing water for agriculture, households, hydropower production, industry, recreation, and wildlife. The river basin includes portions of the states of Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California. Much of the native flow is exported from the drainage basin; over 90 percent of use by California, the largest single user of Colorado River water, is outside the basin. Mexico receives by treaty about 10 percent of the average flow, utilizing basin water for irrigation and municipal use in the Mexicali Valley. The river mouth at the Gulf of California is now dry except during unusual high flow events.

Increasing competition for Colorado River water from within and outside the basin is stimulating searches for new supplies and consideration of changes to the institutions which have dominated river allocation for the past century. Southern California urban areas, already the largest municipal users of basin water, are projected to grow by up to 4 million people by the year 2010, while Arizona has recently begun significant withdrawals for the Central Arizona Project. Accelerated development of upper basin energy resources remains a distinct possibility, with corresponding implications for upper basin water demand. Development of water resources for municipal and agricultural uses in the upper basin continues, leading to concern that provision of adequate supplies may be possible only by developing new sources outside the Colorado River basin.

One alternative for meeting new demands, particularly if existing patterns of use are economically inefficient, is reallocation of existing basin water. In the age of perestroika and budget deficits, approaches which change the roles of traditional institutions in the name of economic efficiency will receive increasing attention.

The Colorado River

The Basin Water Resource

Basin river flows are highly regulated by a series of mainstem and tributary dams, most notably Hoover Dam and Glen Canyon Dam. Total storage capacity presently exceeds 60 million acre-feet (maf), with potential active storage in the two major reservoirs, Lake Mead and Lake Powell, of almost 50 maf (MWD, 1988). (All abbreviations and units are summarized in the List of Abbreviations, Units, and Definitions.) The average annual supply, typically measured as estimated virgin river flows at Lee's Ferry (just below Glen Canyon Dam) is presently estimated to be 13 to 15 maf. Because basin storage capacity is four times annual virgin flows, annual fluctuations in river flows are now of much less importance than multi-year average flow levels.

Estimates of the average annual flow have been revised downward significantly since the first interstate allocation of Colorado River water in 1922. The mean annual flow at Lee's Ferry for the fifteen years preceding 1922 was 18.0 maf, and it was apparently believed that the long term average was at least 16.4 maf/year (Hundley, 1986). The mean upper basin flow from 1906-1983 was 15.1 maf (with the median ten-year average only 14.5 maf), and it is now believed that river flows early in the century were abnormally high.

There is evidence that the present century has also had unusually high flows. Reconstructions of river flows since 1560 from tree ring data indicate average annual flows of 13 maf (Stockton, 1975). Numerous estimates are now used, with 14 maf annually at Lee's Ferry a typical figure.

Basin Water Users

Consumptive use of Colorado River water is made by all seven states in the drainage basin.[1] California is the largest user, with annual depletions of about 5 maf. Consumptive use in Arizona now exceeds 2 maf with the start of diversions for the Central Arizona Project. The third lower basin state, Nevada, uses less than 0.2 maf/year. Colorado is the largest upper basin user, annually depleting available flows by nearly 2 maf, with Utah next at about 0.8 maf. The remaining upper basin states, New Mexico and Wyoming, have annual consumptive uses of about 0.5 and 0.4 maf, respectively (USBR, 1986b). Deliveries to Mexico are fixed by treaty at 1.5 maf. With these levels of use, basin water resources are probably fully utilized, with new uses possible only by reallocation from existing consumptive uses. Table 1.1 summarizes the estimates of present and future requests for basin water in relation to typical available supplies. Significant additional development above present levels will almost certainly lead to the Colorado becoming, in United States Bureau of Reclamation (USBR) terminology a "deficit river" (Reisner, 1986).

Table 1.1 Comparison of available basin flows and present and future consumptive use requests.

Estimated virgin flow	-	14.3 - 15.6
Reservoir evaporation	-	1.7 - 1.8
Available flow	-	12.6 - 13.8
1990 requests	-	12.9
2010 requests	-	14.9
2030 requests	-	15.6

All figures in maf, calculated from input data for this study.

Flow levels are the historic lower decile, and median ten-year averages, respectively. The lower flow level also approximates mean flow levels reconstructed from tree-ring data by Stockton (1975). Requests include annual deliveries to Mexico of 1.5 maf.

Lower basin flows of about 1.2 maf are included; Gila River flows and requests are excluded.

Beneficiaries of Consumptive Uses

Colorado River water is intensively used throughout its length, with irrigated agriculture and municipalities the traditional beneficiaries. The largest single use sectors are located in California, while the largest population within the actual drainage basin is in the state of Arizona. The All-American Canal delivers 3 maf annually to agricultural users in the Imperial and Coachella Valleys of southern California. Up to 1.3 maf is pumped to the major metropolitan areas in southern California through the Colorado River Aqueduct. The largest concentration of upper basin use is along Colorado's Front Range, where transmountain diversions eastward through the Rocky Mountains and across the continental divide supply nearly 0.7 maf annually for agricultural and municipal uses.

Beneficiaries of Nonconsumptive Uses

Nonconsumptive uses of basin water may be of equal economic importance to consumptive uses at the margin. Basin hydropower generation is typically 1.2×10^{10} kilowatt-hours (kwh) (USBR, 1986c), worth

[1] In addition, some basin water passes in wet years via transbasin diversions in Colorado and New Mexico to water users from Nebraska to Texas.

$420 million when valued at $0.035 per kwh, the average avoided cost for base-load power by users of basin hydropower. Using this conservative value - which neglects additional benefits for satisfying peak demands - upper basin water is worth $44/af for hydropower production alone.

The quality of Colorado River water may also be a significant concern. High salinity levels reduce crop yields to irrigators and shorten appliance lifetimes for municipal users. Because upstream water additions lower downstream salinity concentrations through dilution, those suffering salinity damages have a nonconsumptive economic demand for upstream water.

Institutions for Allocation of Colorado River Water

Colorado River water is allocated by state water laws, national legislation, interstate compacts, judicial decree, and an international treaty. Together these laws, judgments, and agreements determine a hierarchy of priorities for users of basin water. Within-state allocations of Western water resources have been regulated under prior appropriation doctrines for over 130 years. Interstate allocation of Colorado River basin water began with the 1922 Colorado River Compact dividing the basin at Lee's Ferry for purposes of apportioning basin water between headwater and downstream states. The upper basin was obligated to deliver 75 maf every ten years, thus giving the lower basin a senior right to an annual average of 7.5 maf. It was anticipated that this would leave 7.5 maf for upper basin use, plus an additional 1 maf for "future" lower basin use (Hundley, 1986). The upper basin was also obligated to provide half of any Mexican delivery obligation. Mexico's claims to Colorado River water were resolved in the 1944 U.S.- Mexico Treaty giving Mexico the right to 1.515 maf annually. This led to the present operational rule of annual releases of at least 8.23 maf from Glen Canyon Dam.[2]

Allocation within the upper basin was agreed upon in 1948, with each state receiving a fixed proportion of the total (variable) upper basin allocation. The relative priority of California and Arizona's allocations was in dispute until 1968 when the Upper Basin Project Act authorized the Central Arizona Project but specified that deliveries would be junior to California's Compact allocation of 4.3 maf. Nearly 0.8 maf used annually by southern California municipalities is water above the basic California allocation. This "surplus" water is the most junior water right in the lower basin, but is fully one quarter of the total water supply for an urban area of 14 million people. Implications of institutional priorities for state water allocations are presented in more detail in Chapter 2.

Objectives

The objective of this research is to test the hypothesis that present allocation of basin water supplies does not result in maximum beneficial use of the resource. This work seeks to estimate the opportunity cost of maintaining existing institutions governing allocation, both at present and in the future. With increasing competition for available supplies, understanding the potential gains from water transfers is necessary in any evaluation of existing institutions.

Methods

Rigorous quantitative estimates of potential economic efficiency gains from relaxing existing constraints to water transfers are made. Second, a qualitative understanding of the most important institutional barriers to efficiency gains is developed. Coupled with an analysis of the existing social and political objectives supporting these institutions, a realistic appraisal of the potential of water transfers to increase benefits of Colorado River water is possible. The role of water markets in achieving transfers which enhance economic efficiency in both consumptive and nonconsumptive uses is considered.

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[2] The Paria River is an upper basin tributary with an annual flow of 20 thousand af; it joins the Colorado River between Glen Canyon Dam and Lee's Ferry, thus giving total annual lower basin deliveries of 8.25 maf.

This research shows the potential and limitations of existing basin supplies in meeting future needs by modeling the performance of alternative allocation institutions under both existing (1985) and projected future (2010 and 2030) supply and demand conditions. Economic demand functions for major demand sectors are developed in order to achieve the objectives of this research. Economic demands are then linked to river flows and institutional allocation rules in a single simulation model. Referred to here as CRIM (Colorado River Institutional Model), it is an optimization model used to estimate the allocations maximizing beneficial use of basin water resources under alternative institutions.

Benefit Estimation

In Chapter 3 water demands for agricultural production in the Grand Valley of Colorado and Imperial Valley in California are estimated. Irrigation in the Grand Valley leaches salts from underlying salt-bearing shales, thus increasing salinity damages to downstream users of river water. Because changes in irrigation and cropping practices can reduce salinity loading in addition to water use, economic demand for both water and salinity production is estimated for the Grand Valley. Linear programs for agricultural production in the Imperial Valley are also included in Chapter 3. Because crop yields and irrigation practices are a function of the salinity concentration of Colorado River water, linear programs are developed at two salinity levels. The difference in profits between models at constant water use provides an estimate of salinity damages; the difference in profits at a single salinity concentration as water use varies gives the economic demand for consumptive water use.

In Chapter 4 the use of basin water for energy production is examined. The economic value of river flows for hydropower generation is first estimated. The economic value of cooling water in production of electric power from fossil fuel based thermal generation is then considered to develop economic demand functions for consumptive use in energy production.

Water demand in southern California municipal uses is developed in Chapter 5. Econometric estimates of household demand functions are obtained from survey data of water use in area communities. Household demand is then used to develop the demand function for southern California municipal use in the region served by Colorado River water.

The River Model

Economic demands and requests (estimated use by sectors where economic demand functions were not estimated) for basin water are linked to physical river flows, salinity concentrations, and the institutional environment by an integrated nonlinear optimization model, CRIM (Colorado River Institutional Model.) The model includes twenty nodes; in the most comprehensive scenario up to fourteen nodes include economic demand sectors. A detailed description of the model formulation is given in Chapter 6.

CRIM is used to estimate water allocations and economic benefits under nine institutional assumptions, from existing institutions based on priorities to a hypothetical market including all identified consumptive use and nonconsumptive use values. Results of model simulations under present and future demand and request levels are presented in Chapter 7. A particularly low flow scenario is included to simulate impacts under severe drought or a long term reduction in average flow levels.

Scope of Analysis and Model Assumptions

This research focuses on direct economic efficiency impacts of alternative water allocation institutions. A national accounting stance is used throughout the analysis. Distributional impacts are presented and discussed, but no formal attempt is made to develop a social welfare function incorporating equity considerations for use in the optimization model CRIM. Indirect, or secondary impacts (pecuniary externalities) are not treated; net benefits or costs from such impacts are thus assumed to be zero in the formal analysis.

Implicit in development of the model are the physical links between all users of Colorado River Basin water resources. Economic values in both consumptive and nonconsumptive uses are included in model formulations. Nonconsumptive use values considered here are the instream use of river water for hydropower production and benefits to lower basin water users of reduced salinity levels in Colorado River water.

A full basin water budget underlies this research. All sources and consumptive uses of basin water are included in the analysis. Most major users of basin water resources are explicitly included as economic actors; the exceptions are noted below. CRIM is a static model, with particular long-term average flow levels used to represent annual flows. This approach implicitly assumes that excess flows in individual years are captured by basin reservoirs and remain available for use in subsequent years.

Institutions, Efficient Allocation, and Models

Optimization models such as CRIM both simulate idealized markets and estimate economically efficient allocations. If hypothesized institutions are likely or possible (rudimentary within-state (consumptive use) water markets, for example) CRIM provides a simulation of impacts of market introduction. Where institutional innovation is unlikely (interstate markets incorporating disparate but physically connected values such as consumptive uses and salinity reduction values), model results are interpreted only as estimates of efficient allocations and benefits from use of basin water resources, given the particular assumptions on the economic values included in the model. A total of nine institutional scenarios are presented, ranging from allocations based strictly on existing institutional priorities, to a hypothetical scenario allowing transfers based on the full set of consumptive and nonconsumptive use values identified in this research.

Economic Valuation

Water values are known to vary widely by use, location, and over time. Standard techniques presented in Young and Gray (1972) are used to estimate economic benefits from specific uses of basin water resources. Residual imputation using linear programming models, and avoided cost are the primary techniques for valuing water use in agriculture and energy production, respectively. Municipal benefits are developed from econometric estimates of household water demand functions, and utilize residual imputation to account for conveyance and treatment costs for Colorado River water.

It is implicitly assumed throughout the analysis that marginal valuation of water use is appropriate. There is concern that transfers of agricultural water may result in retirement of a broad class of crops, and, by implication, water values. In contrast, the use of linear programming techniques here to value water use in agriculture assumes that marginal values alone reflect the opportunity costs of transfers from agricultural uses.

A long run perspective is generally taken. Costs of production in agriculture include all capital costs; resulting derived water demands are true long run estimates. Valuation of hydropower assumes that all capital costs of alternative generation sources are sunk costs. This is most valid at present with excess capacity in the western United States, but may significantly underestimate avoided costs in the future. Capital costs of refurbishing dam power plants are also not considered. Water demand for energy production from fossil fuels is derived using the capital costs of water saving technologies. Capital costs of municipal conveyance and treatment facilities are not considered. These costs have already been incurred; only recurring and operations and maintenance costs of water treatment and delivery are included in municipal water demand estimates.

Except where explicitly noted, all values used are expressed in 1989 constant dollars. Dollar estimates from previous years are typically adjusted using the implicit GNP deflator.

Level of Analysis and Economic Actors

The analysis presented in this research focuses on water allocation at the basin and sub-basin level. Water shortfalls and benefits from institutional innovation in the full basin and in upper and lower basins of the Colorado River are the primary focus. Local impacts, including shortfalls in single years, are generally not available through this research. Similarly, impacts to Mexican water users of changes in water quality (or quantity in one case considered) are not considered and do not affect model results.

Economic consumer or producer surplus measures are the basis for the allocations and benefits estimated by CRIM. Economic surplus measures are explicitly developed for the Grand Valley (Colorado), Imperial Valley (California), southern California municipalities, cooling water for fossil fuel energy resources (coal fired electric generation, coal gasification, and oil shale) in northwest Colorado, and hydroelectric generation at Glen Canyon, Hoover, Davis, and Parker Dams. The level of all other basin water demands and requests use data developed by the USBR (1986b) for use in its Colorado River Simulation Model, or CRSM (USBR, 1986a).

Derived demand functions developed for the Grand Valley and Imperial Valley are extended to the additional major agricultural sectors in the upper and lower basins, respectively. These agricultural users together account for 7.8 maf of the estimated total (United States) Colorado River basin consumptive use (not including reservoir evaporation) of 11.4 maf in 1990. The high level of aggregation in estimation of agricultural water demands is undesirable, but resource and time constraints precluded more detailed study.

The largest diversions not included as economic actors are the Central Arizona Project, with 1990 estimated diversions of 0.85 maf, and transmountain exports to the Colorado Front Range estimated at 0.7 maf (USBR, 1986b). Economic demands and requests (water used in sectors in which economic demand functions were not developed) for basin water are estimated for years 1990, 2010, and 2030.

Allocation of basin water to economic demand sectors is estimated by CRIM through maximizing economic surplus of the included demand sectors under the relevant institutional constraints. Under certain institutional scenarios, economic demands are met by definition, up to some maximum consumptive use level. Consumptive use requests not included in economic demand sectors (3.6 maf in 1990) are met according to existing institutional priorities. The resulting allocations are then fixed as alternative institutional scenarios are considered. Nonconsumptive uses other than hydropower production and salinity reduction are not formally considered in the analysis.

Hydrologic Modeling

Ten-year average water flow levels are used as the basin water supply. Use of such a long-term average is appropriate given basin reservoir storage of approximately four times average annual flows. Two flow levels are considered. The first is constructed from historical flow records for the period 1906-1983; this flow level is below the historic mean, but is very near the long-term mean flow levels reported by Stockton (1975). The long-term flow estimates are reconstructed from tree-rings; the record reaches back to year 1560. The second flow level simulates drought under the long-term flow estimates and is used to estimate the performance of alternative water allocation institutions under stress. An alternative interpretation of the lower flow level is a climate change induced reduction in mean flows (see, for example, Gleick, 1989).

Combined with the water demand levels for 1990, 2010, and 2030, the two flow levels determine six model definitions. Constant salinity inflows calculated from annual averages in the period 1976-87 are used for all model definitions.

During the low flow periods specified above, basin reservoirs are expected to be drawn down to meet shortfalls in filling requests for basin water. Simulations of basin reservoir operations (USBR, 1986c) are used to estimate the level of additional supplies from storage under alternative model definitions. Because reservoirs are drawn down under low flow conditions, evaporation from basin reservoirs is given as a function of flow levels.

The model formulation is static and thus unable include impacts of short-term events, or lags within the hydrologic system. For example, impacts of changes in salinity loading are known to be significantly lagged: reductions in upper basin salinity loading may not result in reduced lower basin salinity levels for several years. This lag is incorporated in CRIM by discounting the value of salinity damages experienced by lower basin water users.

Model Sensitivity

Certain model estimates of basin water allocation and economic benefits under alternative institutional scenarios are particularly sensitive to the estimated economic demand functions. The distribution of water allocations between upper and lower basins under institutional scenarios including only consumptive use values are strongly dependent on the relative marginal values in upper and lower basin agricultural water uses. There is considerable uncertainty about the relative levels of these values, particularly under significant supply reductions from present levels. Water demand for upper basin agricultural uses is extrapolated from estimated Grand Valley demand; this significantly overestimates residual water values where large conveyance and/or pumping costs are incurred in delivery of irrigation water. The effect would be exacerbated by rising energy prices. Upper basin agricultural water values are further overestimated by the assumption that salinity production occurs only in the Grand Valley. Crop acreage limits imposed on the Grand Valley linear programming model impose an upper bound on water transfers from the upper basin; this constrains the level of transfers under institutional scenarios including hydropower and salinity reduction values.

The magnitude of total economic benefits from water transfers is largely dependent on marginal benefits of consumptive use and salinity reduction to southern California municipal water users. These benefits in turn are dependent on the cost and availability of alternative California water supplies, a topic beyond the scope of this research. Energy price levels and base load to peaking power ratios are important in valuing basin hydropower production. In turn, hydropower values significantly affect marginal benefits of upper to lower basin transfers.

CHAPTER 2
THE COLORADO RIVER: DESCRIPTION, ALLOCATION, AND ALTERNATIVE INSTITUTIONS

The Colorado River basin drains an area covering much of the southwestern United States including portions of Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California (see Figure 2.1). Use of river water extends from transbasin diversions high in the Rocky Mountains to irrigated farms in Mexico. Originating from glaciers in the northern Wind River mountains of Wyoming (the Green River) and summer snow fields in Rocky Mountain National Park in Colorado (the upper Colorado River), the river flows over 1400 miles to its mouth in the Gulf of California. In recent years river water has reached the Gulf only in high flood years; typically it is used to extinction.

Entitlements to use of basin water are fundamentally based on the division into upper and lower basins at Lee's Ferry in Arizona. Upper and lower basin states were each given rights to use approximately half the virgin river flow at Lee's Ferry under the 1922 Colorado River Compact. A much smaller allocation is granted by treaty to Mexico. In practice, upper basin use remains below Compact levels, while California has consistently utilized much of the resulting "surplus."

Studies of Colorado River allocation have typically examined behavior of existing institutions during drought or increased development, issues in reservoir management, and economically efficient allocations of the basin water resource. Recent work on economic allocation of Colorado River water has focused on differences in marginal benefits among consumptive and nonconsumptive uses of basin water. The rationale for allocations based on economic values, and the results of studies which include selected economic sectors are presented below.

Physical Characteristics

The Colorado River basin drains an area of 244,000 square miles (figures in this section are from U.S. Department of Interior, 1989 unless stated otherwise) with an annual average flow of 13-15 maf at Lee's Ferry; the range reflects uncertainty about flow levels preceding the historical record. The upper basin includes 44 percent of the total basin area but generates 90 percent of Colorado River flows.[3] Annual virgin flows at Lee's Ferry are highly variable, ranging from 5.0 to 23.8 maf (USBR, 1986b) in the period 1906-1983. While the Colorado River is the dominant water supply for much of the southwestern United States, it is not a particularly large river. For perspective, the Columbia River in the pacific northwest drains a similar area (258,000 square miles), but has a flow of 180 maf/year, over twelve times that of the Colorado. While the Colorado's flow reflects an annual average runoff from the basin land area of only 1.2 inches (or 1.2 acre-inches/acre), the average runoff in the Columbia River basin is 13.1 inches/year. As a further comparison, the Delaware River in the northeast United States produces roughly the flow of the Colorado, 14 maf/year, but drains only 12,000 square miles.

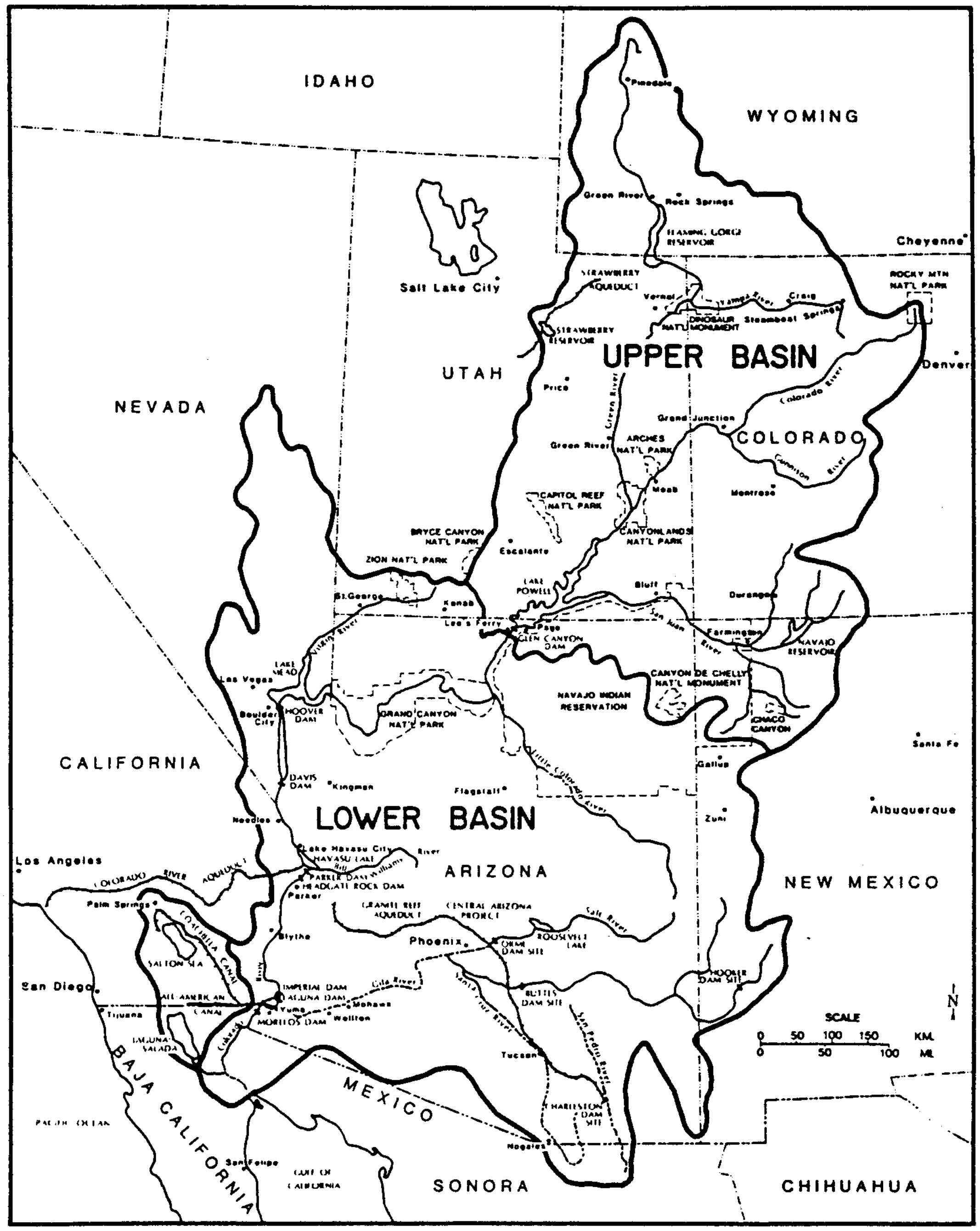
Extremes in climate are a significant characteristic in the Colorado River basin. Temperatures can range from -50°F in the northern mountains to nearly 130°F in the deserts of southern California and Arizona. The highest mountain areas experience frost throughout the summer, while the lowest desert areas are nearly frost free and can grow (with irrigation) a variety of winter vegetable and citrus crops.

The Salinity Problem

Elevated salinity concentrations in the lower basin may cause significant economic damage. Actual salinity concentrations are determined by natural sources, salt loading from irrigation return flows, concentration from consumptive uses, including reservoir evaporation, and water flow levels. The pattern of

[3] All flow figures exclude the Gila River system in Arizona. Except for flood years Gila River water is fully used within the state of Arizona and does not add to Colorado River flows.

THE COLORADO – RIVER OF CONTROVERSY



The Colorado—River of Controversy

Figure 2.1. Upper and lower basins of the Colorado River. (Source: Weatherford and Brown, 1986.)

reservoir operations may also significantly impact downstream salinity. Recent salinity levels at Imperial Dam have ranged from about 900 milligrams dissolved solids/liter (mg/l) in 1956 and 1970 to 577 mg/l in 1986.

Water quality is highly variable along the course of the river. Runoff from high mountain areas in the basin can have salinity concentrations as low as 50 mg/l (Taylor, Weatherford, and Thorson, 1986), while the San Rafael and Virgin Rivers (both tributaries) have typical salinities of 1,500 mg/l. Natural salt springs (often 2,000-3,000 mg/l) also contribute significantly to the total salt loads.

Historical Development

The Colorado River has been utilized for economic purposes by non-native people since the middle of the nineteenth century. Its earliest uses were primarily in mining and irrigation. Early development for irrigation occurred on the mainstem and by transbasin diversions from both the headwaters and the lower basin near the Mexican border. This early pattern largely parallels present development.

The development of Colorado River water for irrigation was foreseen during the John Wesley Powell expeditions in 1869 and 1871 (Powell, 1875). Extensive use of lower Colorado River water began in 1901 with river water diverted from the basin through an ancestral riverbed for irrigation in California's Imperial Valley. Three hundred thousand acres were reportedly under irrigation by 1916 (Hundley, 1986). Significant upper basin diversions were contemplated as early as the 1870's for irrigation of eastern Colorado land. Gravity diversions of Colorado River water from high basins through lower passes to the east began in the periods 1890-1910, with 12,000 af/year passing through the Grand River ditch by 1910 (Cole, 1948). It is noteworthy that these two very early uses of Colorado River water were outside the basin. Today over 5 maf of water is exported from the basin, mostly to the Imperial Valley, southern California municipalities, and eastern Colorado. Uses within the basin also date from a similar period. For example, decrees for irrigation in the Grand Valley in western Colorado date from 1882 (Gardner, 1983).

Hoover Dam, the first massive storage project (and hydropower facility) was completed in 1935. With delivery of basin water in 1941 to Los Angeles via the Colorado River Aqueduct and to the Imperial Valley through the new All-American canal, much of the lower basin infrastructure was in place (Hundley). Glen Canyon Dam, just upstream from Lee's Ferry is the major upper basin storage facility and was completed in 1963. Today the heavily regulated river might be considered a 1,400 mile long plumbing system (Fradkin, 1987).

Institutional Setting

Interstate allocation of Colorado River water is governed by a complex web of compacts, treaties, and court decisions, with the resulting application frequently referred to as the "law of the river." Intrastate allocation operates within the structure of the prior appropriation doctrine prevalent in the western United States. Despite its complexity, remaining ambiguities, and the competing interests of individual basin states, the law of the river has provided a framework under which intensive development of basin water resources has been possible (see Bloom, 1986).

Water Quantity

The 1922 Colorado River Compact was the first agreement between basin states on interstate allocation of the river, superseding the prior appropriation doctrine. (This section is based largely on Hundley, 1986.) Motivating the signing of the Compact by representatives from the seven basin states was the desire to limit the appropriation by a rapidly growing California. The Compact stipulates a delivery by the upper basin of 75 maf in each ten year period, with Lee's Ferry, Arizona defined as the upper-lower basin boundary. The Compact superseded the prior appropriation doctrine only in allocating water between the upper and lower basins, and Arizona refused to ratify because it was not provided safeguards against rapid California development of the lower basin's water allocation.

Specific division of the lower basin's allocation was suggested in 1928 by the Boulder Canyon Bill giving congressional authorization for construction of Hoover Dam. Allocation of 4.4 maf to California, 2.8 maf plus Gila River flows to Arizona, and 0.3 maf to Nevada was suggested but not required by the legislation, and was rejected by California. The 1963 Supreme Court decision in Arizona v. California ruled in Arizona's favor by upholding this early division. Later legislation (1968 Colorado River Basin Project Bill) authorizing construction of the Central Arizona Project (CAP) gave Arizona the means to use its full allocation but stipulated that CAP diversions be junior to California's 4.4 maf right. Surplus flows above 7.5 maf were to be shared evenly by California and Arizona.

Allocation of Colorado River water to Mexico was settled in 1944 with the U.S. - Mexico Water Treaty guaranteeing 1.5 maf to Mexico. With this additional obligation the river was fully appropriated, assuming the 16.4 maf annual flow envisaged with the signing of the Compact. It was soon clear, however, that this figure overestimated average flows by at least 1.5 maf; to protect its claim to a share of the lower basin allocation, Arizona signed the Compact in 1944.

The upper basin states agreed in 1948 to allocate their share by proportions, given the uncertainties in the total upper basin allocation under the Compact and Mexican delivery obligations. This division gave 52 percent to Colorado, 23 percent to Utah, 14 percent to Wyoming, and 11 percent to New Mexico.

Water Quality: Salinity

The quality of Colorado River water is physically dependent on the level, nature, and location of development of basin water. The law of the river may include the impacts of water allocation decisions on salinity levels through the 1974 Colorado River Basin Salinity Control Act. At the present time water quality is seen by Colorado River users as the responsibility of the federal government. Maintenance of water quality at 879 mg/l or better at Imperial Dam (the 1971 level) as specified in the Salinity Control Act is to be achieved by a series of federally financed projects, none of which contemplates reduction in consumptive use of basin water. Similarly, limiting salinity concentrations of Mexican water deliveries to 115 ± 30 mg/l as specified by the 1973 Minute 242 between Mexico and the United States is viewed as a national obligation. The most dramatic example is the Yuma desalting plant, designed to allow crediting of annual Wellton-Mohawk project return flows of 108,000 af (U.S. Department of Interior, 1989) to the Mexican delivery obligation. Because of their very high salinity concentrations, untreated Wellton-Mohawk return flows cannot be used by Mexican irrigators.

The Salinity Control Act and Minute 242, if enforced, together may put an important constraint on the nature of future basin water development. For example, impacts of limits to salinity concentrations on upper basin energy development were a topic of significant concern in the middle 1970's (see Weatherford and Jacoby, 1975).

Instream Values: Hydropower Production

Significant electric power is generated by hydroelectric plants at basin dam sites. While operational rules under which basin reservoirs are managed typically ensure maximum production, basin water allocation decisions do not generally include consideration of hydropower benefits. In particular, institutions which recognize the benefits of reductions in upstream consumptive uses for downstream hydropower production are lacking. Management of basin water for hydropower production is typically limited to maintaining reservoirs above minimum power pool levels to allow hydropower production, and utilizing hydropower plants for peaking as well as base load generation.

Institutional Change and Colorado River Allocation

Societies' approaches to water development and allocation have traditionally recognized the unique role of water in enabling and sustaining life. Water is rarely viewed as just another natural resource, and the institutions governing its use reflect this view. Boulding (1980) observes the profound differences in institutions governing oil and water development and speculates that "the sacredness of water as a symbol of ritual purity exempts it in some degree from the dirty rationality of the marketplace."

Traditional water development has focused primarily on increasing consumptive uses. While western water institutions have achieved considerable success in facilitating substantial growth in consumptive water uses, they have been less useful in fostering measured use of limited supplies and reallocation to new uses, both consumptive and nonconsumptive. The traditional view was well expressed by Floyd Dominy (1965):

> The needs of a booming population and economic growth have escalated water needs at a rate which makes it more important today than ever to put every last drop of water to use before it reaches the sea or evaporates.

The dominant philosophy has been to provide for new demands through wringing ever more undeveloped water from wherever it might be found. This approach is likely to be successful in an immature water economy, but may become untenable when marginal costs of increased supplies substantially exceed the ability to pay of beneficiaries (Randall, 1981). The result of rigid allocation rules and a mature water economy could be a very real water crisis.

Water Marketing

It has been widely suggested by economists and others that water crises might be averted at relatively little cost by allowing water allocation to be subject to market transactions (see, for example Anderson, 1983a). If properly structured to include consideration of physical externalities in water transfers, allowing market forces to enter water allocation decisions could substantially increase supplies available for new uses while protecting existing water rights holders (Shupe, 1986; Anderson, 1983b). There is important evidence that markets can in fact lead to water transfers enhancing economic efficiency (Howe, Schurmeier, and Shaw, 1986a). The significance of physical and pecuniary externalities in impeding water transfers is addressed by Hartman and Seastone (1970) and offered as an explanation for the limited number of water transfers which are observed (Young, 1986).

Proposals for specific institutional innovations to encourage better functioning of water markets have been offered (Howe, Schurmeier, and Shaw, 1986b). Institutions for encouraging transfer of small quantities of salvaged water are largely absent, but are one example of change which could be important in increasing economic efficiency of water use (Getches, 1987). Where annual supply fluctuations are large, options for secure rights may be attractive to municipalities (Michelsen, 1988).

A growing body of empirical work has identified the level and cost of market reallocations which would be required to satisfy a variety of consumptive and nonconsumptive water demands. Those of relevance to this research are discussed below.

Interstate Transfers

Western U.S. water resources have traditionally been allocated by the individual states. Where interstate allocation has been required, in the Colorado River basin for example, setting of individual state entitlements has required extensive negotiation and carefully worded agreements between the states. The resulting allocations have generally been viewed as inviolate, though recent attempts have been made to implement interstate transfers of Colorado River water. In the first instance, the investors in the so-called Galloway proposal sought to permanently transfer perfected upper basin water rights to increase the reliability of water supplies to San Diego (Gross, 1985; Bird, 1987). A more recent proposal (Martz, 1990) by private investors under the name Resource Conservation Group seeks to sidestep the Colorado River Compact allocations through the use of long term leases.

Recent legal decisions may point towards a decreasing ability of state water law to restrict interstate water transfers. The 1982 U.S. Supreme Court decision in Sporhase v. Nebraska found groundwater to be an article of commerce and prohibited state regulation for the sole purpose of prohibiting interstate transfers (Smith, 1987). Chan (1988) speculates that the decision may in fact hasten market based interstate transfers of other water resources. Further weakening of state water laws occurred with the 1990 U.S. Supreme Court decision in California v. FERC affirming the right of the federal government to supersede state water law in regulating hydroelectric power plant operation (Kirsch, 1990). The decision overturned state mandated minimum instream flows in conflict with a hydroelectric plant license.

Legal developments thus point to an increased probability that the water allocations specified in the Colorado River Compact may in the future be subject to change. This could occur either by direct challenges at the federal level to states' authority to restrict transfers, or through states lowering barriers to transfers in order to forestall federal intervention. It is likely that challenges to Compact allocations would be motivated by anticipated water shortages in areas with relatively high water values. Such proposed transfers would seek to exploit the present disparities in economic value of basin water.

Economic Justification and Impacts of Water Transfers

A well-behaved market equalizes commodity values across different uses. In doing so, commodities are transferred from lower valued to higher valued uses until equilibrium prices and allocations are established. At this equilibrium, no party can be made better off without causing at least one other party to be made worse off. Such a state is defined as a Pareto optimum. This work will assume that such outcomes are desirable relative to allocations preserving disparities in Colorado river water values.[4] Burness and Quirk (1980) give a formal statement of the conditions under which water transfers of Colorado River water would be economically efficient.

The optimization model CRIM presented in this work includes only direct benefits and costs of utilizing basin water, and thus simulates market allocation across the modeled sectors. The conditions under which only direct benefits and costs should be included in evaluation of water transfers are discussed by Howe and Easter (1971) and Eckstein (1958). Conditions for inclusion of indirect, or secondary benefits and costs include the presence of significant unemployment and fixed capital investments. This study thus assumes nearly full employment across basin water users. Water project investments are viewed as sunk costs financed by federal monies, eliminating the need to consider secondary impacts of large capital investments. While the impact of secondary effects often dominates debate on changes in water allocation, the approach taken here is also consistent with that advocated by McKean (1958) and the U.S. Water Resources Council (1973).

Given net secondary impacts of zero, water reallocations determined by CRIM must satisfy the Kaldor-Hicks compensation principle. Under this criterion a social state A is preferred to state B if those better off in state A could compensate those worse off in A such that everyone is better off in A compared to B. Any change from A to B would then be called a potential Pareto improvement. Model solutions are thus potential Pareto improvements, to the extent that net secondary impacts are indeed negligible.

There are significant limitations to this approach. Any judgement on the desirability of different water allocations must implicitly rank different social states. Modern welfare theory makes it clear that such judgments cannot be made in a completely satisfactory way. Insistence on non-comparable utilities leads to the conclusion that only dictatorial ranking can give a complete ordering of social states (Arrow, 1951).

Potential Pareto improvements do not require actual payment of compensation.[5] Without this requirement both gainers and losers result from any significant change. If the change is not considered equitable by societal standards (losers are initially less well-off than gainers or, perhaps, losers outnumber gainers) then the change may not represent an improvement.[6] Adding benefits and costs across individuals tests for economic efficiency improvements, but provides no insight into equity concerns.

Impacts not readily expressible in monetary units are termed intangibles, and will generally be present in any proposed water transfer. These cannot be quantitatively compared to economic benefits and costs, but can be real and significant. Examples are community values and environmental impacts. Reservations about the role of markets in water allocation based on equity and community value impacts are expressed by Nunn (1989). Environmental values of particular relevance to the Colorado River are articulated by Nash (1986).

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[4] This abstracts slightly from "optimal" differences in water value caused by physical factors such as evaporation and potential energy.

[5] While the principal parties to a market transaction are presumably made better off, there will always be parties bearing secondary benefits and costs.

[6] Little (1957) proposes that state A be preferred to be B if benefits exceed costs and equity is improved.

Forums likely to be sensitive to impacts not represented in market transactions are discussed in Nunn and Ingram (1988).

Research on Colorado River Water Allocation

The Colorado River may be one of the most intensively studied free flowing water courses in the world. As the dominant water supply for a half dozen western states in the driest region of the United States, and a crucial component of the California state water budget, basin water is a pivotal regional resource. Despite its recognized importance, relatively little formal work has been done on impacts of alternative water allocation institutions. In addition, most work has focused only on consumptive uses of basin water, or on selected issues such as salinity control. Little work has considered the full range of consumptive and nonconsumptive use benefits from basin water resources.

The study Water and Choice in the Colorado River Basin (National Academy of Sciences, 1968) provides a comprehensive view of possible objectives in management and allocation of basin water. It concludes that institutions must recognize economic efficiency, income redistribution, political equity, and environmental concerns as objectives in use of basin water. It suggests that outcomes of proposals for institutional change which address these goals should always be compared to those with national economic efficiency as the sole objective. Performance criteria for such institutions are suggested by Fox (1976). Kneese and Bonem (1986) and Clyde (1986) provide useful analyses on the response of basin water allocation institutions to increasing demand and severe drought, but are limited by the high level of aggregation in their analyses.

Reservoir Management

One line of study has focused on improving basin reservoir management within existing institutional constraints. Jensen (1976) uses a model of surface water hydrology and salinity to show that small reductions in shortages are possible through operating strategies which reduce reservoir evaporation losses. Changes in flood control strategies to allow better use of water in high flow years are shown in a USBR (1986c) report utilizing the Bureau developed Colorado River Simulation System to result in more frequent use of "surplus" water. A similar result is shown by Brown, Harding, and Lord (1988) utilizing a mixed integer programming model of the Colorado River basin. The authors of these studies do not attempt to measure lost drought protection and flood control benefits from events which do not arise in their particular flow scenarios. While small gains appear possible through improved management, these supply increases appear small relative to anticipated future demands.

Economic Allocation for Consumptive Uses

Projections of rapid growth in southern California urban populations, and California's loss of nearly 1 maf of previously surplus Colorado River flows with completion of the Central Arizona Project have prompted several studies of economically efficient sources of new supplies for the growing urban area. Wahl and Davis (1986) consider both costs and institutional constraints of several possible transfer schemes, including reallocation of river flows from Imperial Valley agriculture to urban use.

In an approach similar to that taken in the present study, Vaux and Howitt (1984) use a nonlinear trade model linking northern and southern California water demand and supply sectors to show that, with minor exceptions, reallocation is less costly than development of new supplies up to the year 2020. Institutional constraints which might limit the proposed transfers are not seriously considered. Very large transfers from the Imperial Valley (1.1 to 1.3 maf) to southern California urban sectors are included in their economically efficient allocations. It is not clear how this water is to be transported, given capacity constraints of the Colorado River Aqueduct.

Complementary work on the Colorado River basin, focussing on transfers of upper basin water, has been performed by several authors. Brown, Harding, and Payton (1989) use a revised priority system based on marginal economic values in different uses with a network model to predict disposition of marginal upper basin flow increases under alternative flow scenarios. A comparison with predicted deliveries under current institutions shows that under future demand levels the economically based priority system greatly reduces the costs of shortages. Their economic model includes estimates of water use values in upper basin agriculture, upper basin exports for municipal use, southern California municipal use, Central Arizona Project diversions. Municipal and industrial salinity damages and the value of hydropower production are also incorporated. All economic demands are assumed perfectly elastic, however, with constant marginal values. Input data on river flows and user request levels is taken from Colorado River Simulation System input data (USBR, 1986b).

Oamek (1990) uses a positive quadratic programming model to estimate upper basin agricultural derived demand for Colorado River water. He concludes that if the Compact were revised to allow transfers, up to 400,000 af of present agricultural water could be transferred annually at a cost of no more than $10/af ($5/af if conversion to dryland hay production is possible), with significant additional transfers possible at slightly higher cost. Using the Colorado River Simulation System he concludes that immediate permanent transfers of upper basin water of 311 kaf annually, rising to 400 kaf after the year 2000 would be sufficient under a normal flow scenario to guarantee deliveries to the Metropolitan Water District of at least 900 kaf, or about three quarters of aqueduct capacity. His analysis is restricted to transfers between upper basin agriculture and hypothetical higher valued lower basin uses. He identifies additional annual benefits of $8.6 million ($24/af of transferred water) from salinity reduction and $7.5 million ($21/af) for hydropower production, based on lower basin salinity damages of $280,000 per mg/l and energy values of $0.015/kwh.

Economic Allocation and Salinity Control

Several studies focus on the problem of salinity levels in Colorado River water. Alternative on-farm salinity control strategies in the Grand Valley were investigated by Gardner and Young (1988). They show that over half of present on-farm salt production (126,000 tons) could be eliminated by irrigation system improvement subsidies at a total cost of $12/ton. They investigate a number of cost-sharing mechanisms giving net economic benefits (considering only salinity) which might be acceptable to both Grand Valley irrigators and lower basin Colorado River users.

Lee (1989) presents three related formal river models to examine salinity issues in the Colorado River basin. The first is used to simulate impacts of federal water subsidies and commodity price support programs on salinity levels. The second is a basin optimization model, maximizing net economic surplus over agricultural producers (including consumptive use benefits and salinity losses) and salinity damages in lower basin municipal and industrial uses. The third model adds stochastic river flows to the first model to estimate impacts of flow variability on salinity levels and returns to water (including salinity damages) in agriculture.

Lee's first model estimates upper basin derived demand elasticities for water of about -1, for up to 20 percent reductions in consumptive water use. Imperial Valley salinity damages are estimated at $9,000 per mg/l at 750 mg/l. Results of the second model show a dramatic water transfer out of upper basin agriculture. The annual direct cost of a water use decline of 87 percent in upper basin agriculture is estimated at $14.8 million, or $17/af. Present consumptive use in the modeled sectors is not given by Lee, but is approximately 1,000 kaf based on data (USBR, 1986b) used in this research. Additional government salinity control costs of $23 million are identified. The total cost of the estimated 1.27 million ton salt reduction is $30/ton. Water reallocations are driven largely by reductions in lower basin municipal and industrial salinity damages as upper basin agricultural water use is reduced.

Contributions of this Research

The research presented in the remaining chapters is the most comprehensive study of economic allocation of Colorado River water resources to date. An integrated optimization model, CRIM, is developed to evaluate policies for increasing beneficial use of basin water resources. The model includes a hydrologic simulation, realistic economic demand functions, and representations of alternative allocation institutions.

This study includes most major consumptive and nonconsumptive uses of basin water in the allocation decision. Up to 7.8 maf of the estimated total 1990 consumptive use of 11.4 maf are included as economic actors, the most of any study using full water demand functions. In addition, economic values of major

nonconsumptive uses in hydropower production and salinity reduction are represented. A wide array of alternative institutions for allocating basin water are formally modeled, from allocation by existing priorities to an interstate market in all consumptive and nonconsumptive uses. For the first time, the role of within-state water transfers for increasing beneficial use of basin water resources is considered using a hydrologic-economic model of the Colorado River basin.

CHAPTER 3
IRRIGATED AGRICULTURE: WATER AND SALINITY

Economic demand for water in agricultural production is estimated in this chapter for the Grand Valley in Colorado and the Imperial Valley in California. Linear programming models including the dominant crops and irrigation practices and technologies for each region are developed, with salinity impacts integrated into the model formulations. In addition to differences in climate and scale, the role of salinity in the two regions is fundamentally different. Crop yields in Imperial Valley agriculture are a function of salinity concentrations of Colorado River water; linear programs at two distinct salinity levels are developed to include salinity impacts. Because salinity concentrations of applied irrigation water are relatively low in the Grand Valley, variations in crop yield with salinity concentrations are small and not considered here. Salinity loading produced by seepage and deep percolation of applied irrigation water is of great concern, however, since the resulting salts increase downstream salinity concentrations. Because reductions in consumptive use and changes in irrigation techniques can reduce the level of salinity loading by Grand Valley irrigators, salt production is included as an integral part of the Grand Valley linear programming model.

Estimated changes in operator profits as consumptive water use is varied are used to develop analytic functions giving regional water demand as a function of water use. The method is an application of the technique of residual imputation. Market values of all non-water inputs are subtracted from gross revenues, with the remaining net revenue taken as the return to water. The Grand Valley profit function includes salinity production levels and is interpreted as the demand for water use and salinity production.

Grand Valley

The Grand Valley lies in extreme western Colorado, bordered by mountains to the west and rugged canyon country to the north and south. The town of Grand Junction (population 50,000) lies at the confluence of the Gunnison and Colorado Rivers in the southeast quarter of the valley. Most of the estimated 60,000 irrigated acres are north of the Colorado River, stretching 25 miles west of Grand Junction. Most irrigation water is supplied by gravity from several major canals diverting water directly from the river. A small part of the eastern valley, particularly on low mesas overlooking the river is devoted to fruit crops; some pumping is required to lift river water to irrigate the mesa orchards.

The Grand Valley is of particular interest because of salt bearing shales which underlie the irrigated land. Seepage and deep percolation from irrigation leaches salts from the Mancos shale, contributing an estimated 500,000 tons of salts to the river each year (U.S. Department of Interior, 1989). The valley is the site of a major canal lining project by the Bureau of Reclamation, and of an equally significant program by the Soil Conservation Service for reducing on-farm seepage and deep percolation. The purpose of both programs is to decrease the salinity production by Grand Valley irrigators. Efforts to date have resulted in an annual decrease in salinity loading of at least 50,000 tons (U.S. Department of Interior, 1989).

Model of Water Demand and Salinity Production

Estimates of agricultural demand for consumptive use of irrigation water and salinity production in the Grand Valley are developed in this section. A linear programming model based on that used by Gardner and Young (1988)[7] is used to obtain point estimates of net returns in typical irrigated farm operations in the Grand Valley as a function of crop consumptive use and total salinity of return flows. A continuous polynomial function in water and salinity is fit to the resulting estimates for use in the full Colorado River model CRIM.

The updated linear programming model includes activities representing major Grand Valley crops, including alfalfa, corn, and irrigated pasture. Pinto beans are included as a higher value crop which is

[7] R.G. Taylor updated and modified the model using new data on crop prices and production costs, and entered the new model in the appropriate computer format.

presently grown in the region. Perennial fruit crops are not included; it is presumed that returns to water and salinity production for these specialty crops are significantly higher than in the represented crops. Modeled crops can be irrigated by up to nine irrigation technology and labor combinations. These are discussed in Gardner and Young. Consumptive water use is assumed independent of irrigation technology; all tailwater losses and deep percolation are assumed to return to the Colorado River for use downstream. Interviews with officials involved in Grand Valley salinity control efforts indicate that virtually all water diverted but not consumptively used returns to the river (Champion, 1990). Retention time by the aquifer is not explicitly considered, but is assumed small relative to the full basin retention time for salinity.

Data and Model Description

The present model was updated using data from several sources. Crop enterprise budgets for 1987 for western Colorado (Dalstead, 1988) were used for all costs except irrigation capital and labor costs. Alfalfa costs include costs of establishment incurred every sixth year. The budgets are based on use of the operator's machinery and labor for field preparation, planting, and harvesting. This is representative of only one type of farming practice in the Grand Valley as many operators make extensive use of more costly custom services (Champion). Crop yields used in the model are based on Mesa County yields for 1988 reported in Colorado Agricultural Statistics (1989). Acreage limits used in the model are from maximum and minimum 1976-1988 reported acreages from the same source. Total irrigated crop acreage in the Grand Valley is based on U.S. Department of Commerce (1988) Mesa County figures for 1987, and includes non-harvested irrigated pasture not included in the state publication. Previous estimates of Grand Valley crop acreage and water consumption do not include irrigated pasture at the levels indicated by these crop statistics. For purposes of this research, a figure of half the irrigated pasture acreage reported by the U.S. Department of Commerce was chosen; it is assumed that this acreage is fully irrigated. The resulting total irrigated acreage estimate is 65,800 acres, of which 12,330 is non-harvested irrigated pasture. Crop consumptive use implicit in Gardner's original linear program was taken from Leathers and Young (1976). The data used in the model is summarized in Table 3.1.

Table 3.1 Summary of characteristics used in Grand Valley model.

Crop	Yield	Units	Price Received ($/unit)	Production Costs[a] ($/acre)	Water Use ($/acre)	Maximum Acreage (acres)
Harvested hay	3.05	ton	74.50	170 - 238	2.68	41,000
Corn for grain	135	bu	2.86	315 - 383	2.21	19,300
Pinto beans	16.2	cwt	20.99	228 - 296	1.74	2,100
Pasture	7.25	AUM	11.00	16 - 184	2.51	12,890

1987 dollars

[a] Production cost variation reflects alternative irrigation technologies. Costs include land rental and irrigation labor costs, but exclude water delivery costs of $4/af.

Total consumptive water use is employed to constrain water in the updated model since only net depletions to the river are of interest to downstream water users. Crop acreages are constrained to maximum and minimum levels based on historical acreage levels, with the exception of irrigated pasture. Pasture acreage is constrained to a fixed proportion of hay plus corn acreage, based on 1976-1988 average acreages for the three crops.

Returns to salinity production are obtained by imposing a constraint on total salinity production. Salinity reduction is achieved primarily by limiting deep percolation. Gardner and Young's model includes labor intensive methods, such as the use of short sets and manual cutback with gated pipe delivery, in addition to capital intensive techniques including ditch lining, gated pipe, and ported ditches. Limits imposed on the use of these techniques in the original model are retained here. Labor intensive techniques are restricted to 30 percent of total acreage, or 19,740 acres. Capital intensive technologies are limited to 90 percent of total acreage, or 59,220 acres. Significant lining of ditches on Grand Valley farms has already occurred as the result of salinity control efforts. Using figures in U.S. Department of Interior (1989), lining of ditches has been accomplished on 7,635 acres, or 12 percent of all irrigated land.

Returns to Water and Salinity Production

Consumptive water use and salinity production are alternately, then in combination constrained to map the response of irrigators' net returns to water and salinity; Table 3.2 shows selected basis changes, net returns, and shadow prices for consumptive water use and salinity production. Note that salinity production, though unconstrained, declines with reductions in consumptive water use. This occurs because total tail water losses and deep percolation are reduced as land is removed from production. With salinity constrained, substantial reductions in salinity production are achieved through ditch lining without changes in cropping patterns. Labor intensive technologies are used in conjunction with land retirement to further reduce salinity production.

Table 3.2 **Selected basis changes of Grand Valley linear program with water use and/or salinity production constraining.**

Use (kaf)	Salinity (1,000 ton)	Net Return (million $)	Marginal Water Value ($/af)	Marginal Salinity Value ($/ton)
163	295	2.73		
152	280	2.57	14.9	
132	230	2.13	22.1	
128	218	1.88	64.5	
163	247	2.50		5.8
163	232	2.38		5.9
162	216	2.25		6.1
162	214	2.14		6.9
162	213			7.5
161	211			8.7
146	185			9.7
140	169			11.0
156	283	2.62	6.0	5.8
150	271	2.51	8.1	5.8
130	207	1.92	46.9	5.8
130	177	1.74	46.7	6.1

1987 dollars

A second order polynomial

$$\pi(x,\sigma) = \beta_0 + \beta_1 x + \beta_2 x_2 + \beta_3 \sigma + \beta_4 \sigma^2 + \beta_5 \sigma x \qquad (3.1)$$

is fit to a set of solutions from the linear programming model. $\pi(x,\sigma)$ is the resulting profit function, x is consumptive water use, and σ is salinity production. For institutional scenarios in which salinity levels do not enter the CRIM objective function, Grand Valley irrigators would seek to maximize returns from water consumption alone without incentive to limit salinity levels. Because changes in consumptive use change the level of salinity production, however, a second polynomial $\sigma(x)$ is used to estimate the resulting salt loads:

$$\sigma(x) = \alpha_0 + \alpha_1 x + \alpha_2 x^2 \quad (3.2)$$

The coefficient estimates α_i are given in Table 3.3. Equation (3.2) is valid only when salinity levels are unconstrained and are reduced merely as a consequence of consumptive use reductions.[8] This represents the case where incentives for salinity reduction are lacking.

Table 3.3 Coefficient estimates for Grand Valley profit functions and salinity production when salinity loading is unconstrained.

	Coefficient Estimates					
Year	constant	w	w^2	σ	σ^2	σw
Profit Functions						
1990	-11,800	82.9	-0.190	0.799	-0.0742	0.133
2010	-13,100	82.9	-0.172	0.799	-0.0672	0.120
2030	-14,500	82.9	-0.155	0.799	-0.0608	0.109
Salinity Production						
1990	-474	7.90	-0.0195			
2010	-523	7.90	-0.0176			
2030	-578	7.90	-0.0160			

1989 dollars

Profits measured in $1,000, water withdrawals w in kaf, salinity production σ in 1,000 tons.
Assumed irrigation efficiency of 50%, $4/af water delivery cost included in coefficient for withdrawals.

Net returns estimated from the linear program are shown together with the profit function $\pi(x,\sigma)$ in Figures 3.1 and 3.2. In Figure 3.1 salinity is unconstrained and profits are shown as a function of consumptive water use, with the salinity level given by equation (3.2) used to calculate profits. Figure 3.2 shows profits as a function of salinity levels; since reductions in consumptive use are one method of reducing salinity production which enters the solutions, consumptive use levels from the linear programming solution are used in equation (3.1) to calculate the profit function.

Present and Future Demand

Demands for irrigation water in years 1990, 2010 and 2030 for use in CRIM are constructed from the profit function in equation (3.1) and the salinity production function in equation (3.2). The linear program results presented above are taken as the basis for the 1990 profit function used in CRIM. Profit functions used in CRIM are based on withdrawals w rather than consumptive use x. Irrigation efficiency of 50 percent for the Grand Valley is assumed in making the transformation. A further adjustment of $4/af for withdrawals

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[8] When salinity production is unconstrained, profits $\pi(x)$ can be estimated directly by $\pi(x) = a + bx + cx^2$, where a, b, and c are constants. This form is used in extending Grand Valley profit functions to other upper basin irrigation demands.

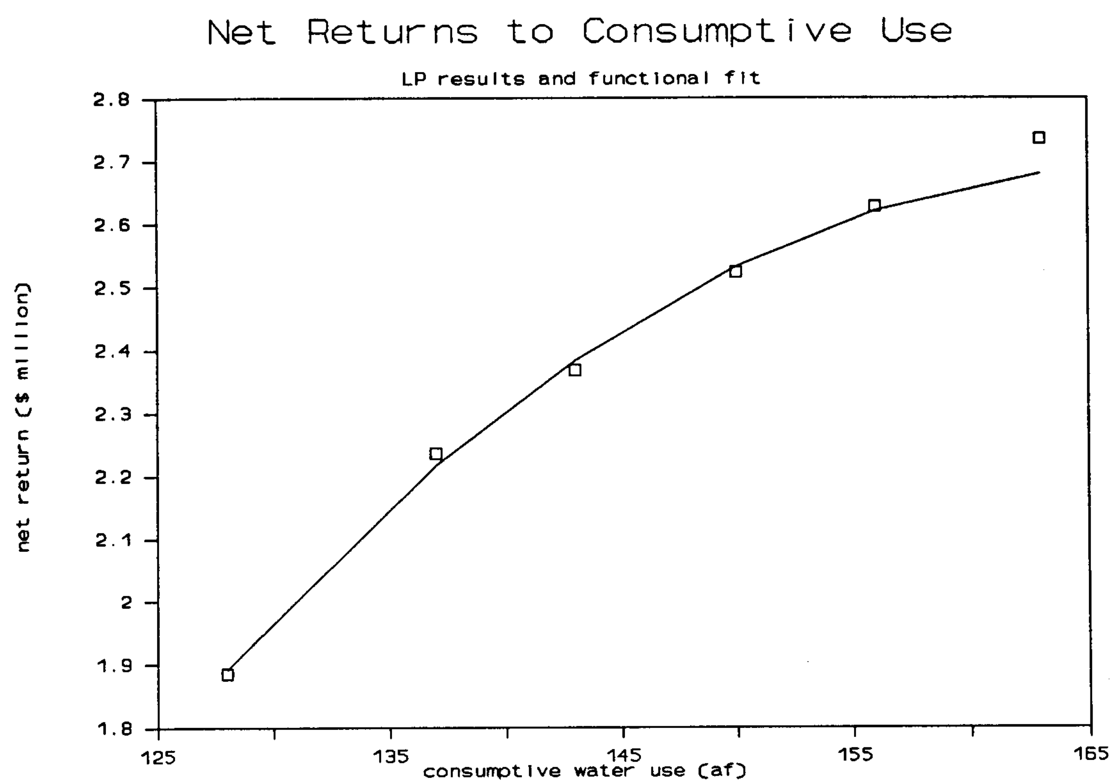

Figure 3.1 Grand Valley profits as a function of consumptive water use with salinity levels unconstrained. (The curve connects the points representing solutions from the linear programming model).

is made to reflect the typical water assessment by the Grand Valley Water Users Association (Klapwyk, 1990), a major ditch company in the Grand Valley. Following Vaux and Howitt (1984), profit functions are scaled for an outward shift in water demand of 0.5 percent per year, the national population growth rate (U.S. Department of Commerce, 1989). Profit function estimates for water withdrawals for years 1990, 2010, and 2030 are given in Table 3.3.

The linear program results incorporate land rental costs, a portion of which are attributable to returns to water. Land rental costs above the minimum level reported by Dalstead are assumed to reflect capital improvements or fertility differences; the minimum rental rate for harvested crops of $18/acre or $6.7/af is taken as a return to water. This adjustment is included in CRIM, but is not shown in Table 3.3.

Discussion

A simple linear program misses many complexities which are important in explaining agricultural factor demands. Heterogeneity of farm size, soil quality, attitudes towards risk, and management expertise makes insistence on constant demand across operators a gross approximation. Many operators may approach farming more as a lifestyle choice rather than a source of income. Most Grand Valley farm operations are too small to produce an owners' primary income; most acreage, however, is concentrated in much larger operations (U.S. Department of Commerce, 1988). This analysis primarily simulates operation of the larger holdings, which are the most likely to be operated as profit maximizing enterprises.

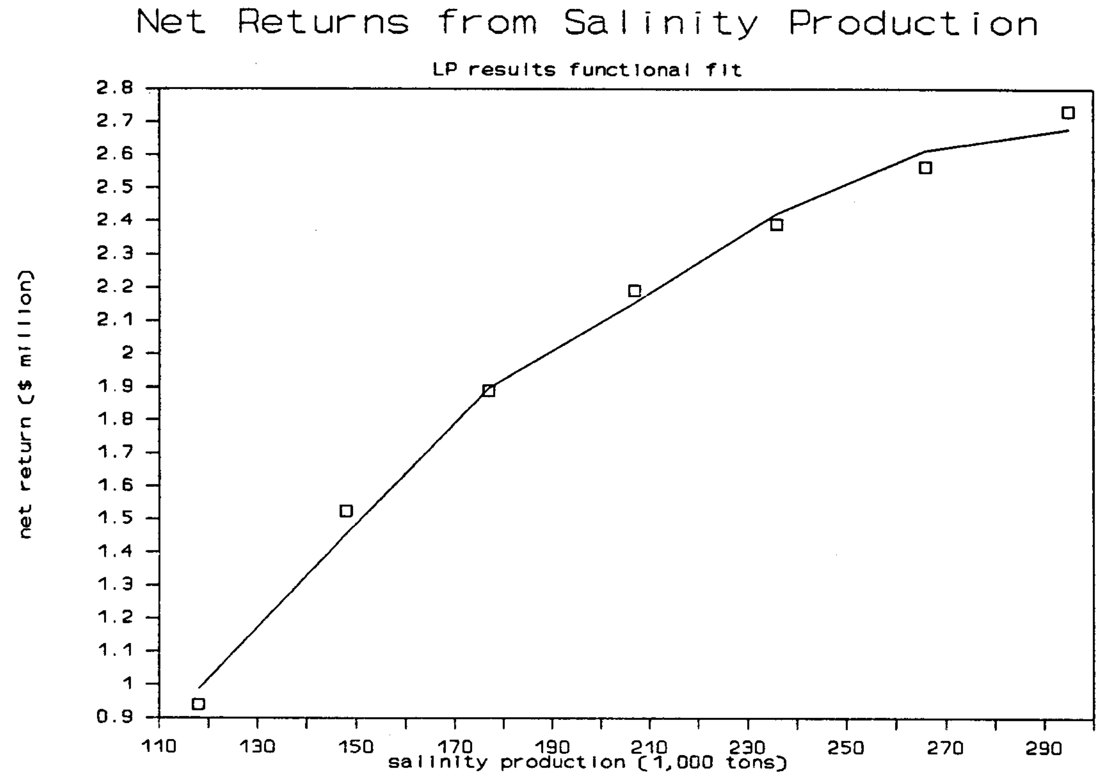

Figure 3.2 Grand Valley profits as a function of consumptive water use with salinity levels unconstrained. (The curve connects the points representing solutions from the linear programming model).

The choices facing operators are not fully represented in a simple model such as that presented here. For many operators reducing consumptive use by switching from pasture to a smaller alfalfa acreage, or from hay to corn are possibilities which may in practice have very small net costs. These choices are not allowed by the model specification since, using the budgets in Table 3.1, each results in a net benefit from reducing water use. Since this is implausible, it is assumed that factors not included in the model restrict these choices. Other low cost adjustments to consumptive use limitations are not included. Some crops enter the model formulation only as broad aggregates, or are excluded entirely. Hay is included as a single crop, but actually includes alfalfa hay and various grass hays. Alfalfa yield is substantially greater than other hays, allowing it greater returns to water than is represented in the model; the value of other hays (those with less than average yields) is likewise overstated. Small grains are frequently grown as cover crops for alfalfa on up to 10 percent of the irrigated acreage. Reliable budgets for these crops could not be obtained so they were excluded. Some consumptive use gains may be possible by moving to more intensive grain production.

The linear programming model limits reductions in consumptive use to 78 percent of full irrigation levels; further reductions violate the minimum acreage constraints imposed (somewhat arbitrarily) on the model. For use in CRIM the profit function $\pi(w,\sigma)$ is defined for consumptive use reductions to 67 percent of full irrigation levels. Salinity production is defined down to 33 percent of maximum levels. Because $\pi(w,\sigma)$ is believed to overestimate water values for large consumptive use reductions, this extension of the valid range for water transfers from upper basin agriculture is justified. For institutional scenarios requiring very large reductions in upper basin use, $\pi(w,\sigma)$ is defined for consumptive use reductions up to 15 percent above the institutionally imposed shortage levels; proportional salinity reductions of twice consumptive use reductions are allowed.

The scope of choices is inevitably limited in models of this type by the investigator. Acreage limits are imposed to restrict model solutions to plausible departures from existing practices. Increasing pinto bean acreage in the model would reduce consumptive use, but is viewed as unlikely given price risks and sensitivity to saline soils.

Changes in consumptive use occur in the model only through changes in cropping patterns. Irrigation techniques alone are assumed to have an insignificant impact. This assumption may be inappropriate on two grounds. First, evaporation losses from water application and in tail water return flows are certain to occur. Further, phreatophytes may utilize tail water. Irrigation techniques would influence these consumptive uses.

Given the caveats presented here, the representation of the model results $\pi(w,\sigma)$ should be used as a rough estimate of Grand Valley demand for irrigation water. The above cautions indicate that the profit function $\pi(w,\sigma)$ is probably an upper bound on the value of water in the Grand Valley.

Imperial Valley

Description

The Imperial Valley is a rich agricultural region, producing a wide variety of feed and vegetable crops. The gross value of agricultural crop production in 1988 was nearly $800 million dollars with 38 different crops valued above one million dollars (Imperial County Agricultural Commissioner, 1989).

Located in a low basin in southeastern California, most of the valley is below sea level, with all drainage into the closed Salton Sea. The irrigated area stretches approximately 40 miles north from the Mexican border to the Salton Sea and is 20 to 30 miles in width.

The typical growing season is over 300 days, broken by an average of eight frosts each winter. Because average annual precipitation is only 2.8 inches (Gardner, 1983) irrigation is required for virtually all agricultural activities. The Colorado River is the only significant source of irrigation water supplies for the 460,000 irrigated acres. In typical years 2.6 maf are diverted from the river at Imperial Dam to irrigate this land.

Demand for Irrigation Water

Demand functions for irrigation water in the Imperial Valley are developed for two salinity levels of Colorado River water. A linear program adapted from Gardner and Young (1985)[9] is used to simulate a variety of single and double cropping practices in the Imperial Valley. The model includes a range of possible adjustments to limited water supplies by irrigators, but does not include improvements to irrigation delivery systems.[10] Estimates of agricultural water demand are obtained from changes in modeled net income to irrigators as water supplies are reduced. The difference in net income at the modeled salinity levels gives estimates of salinity damages as a function of water use. A continuous function approximating the dependence of modeled net income on water deliveries is derived for use in CRIM.

The linear program employed here closely follows that of Gardner and Young (1985); crop prices, production costs, and acreage limits have all been updated. The model retains most cropping and irrigation practices described in the original model. These include alternatives for cover crops in alfalfa stand establishment and numerous double cropping possibilities. Crop yields, prices, water requirements, and

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[9] R.G. Taylor performed much of the work in updating the model.

[10] Technical improvements to delivery systems are possible and politically acceptable (MWD and IID, 1988, and Reisner and Bates, 1989) but are not included in the formal model. It is assumed here that flexibility in water use inherent in the model can be accomplished at lower cost than structural improvements to delivery systems.

production costs are shown in Table 3.4. Upper and lower acreage bounds for each crop type are also included; note that alfalfa acreage is not constrained. Crop yields at modeled salinity levels (reported in Gardner, 1983) and water requirements from the original model are retained here. Crop prices are 1982-88 (real price level) averages (Imperial County Agricultural Commissioner, 1982-87), adjusted to 1987 dollars by the GNP deflator. Production costs are taken from Imperial County Cooperative Extension (1988) crop enterprise budgets for 1987. The budgets mostly use custom rates which reflect typical practices for vegetable crops; they may substantially overstate costs for alfalfa, however. Ranges on crop yield are the result of the two soil types included in the model and the impact of differing salinity levels. The range of production costs reflect differences in harvest cost with varying yields, and irrigation cost differences with frequency of irrigation.

Table 3.4. Summary of characteristics used in Imperial Valley model.

Crop	Yield 800 mg/l (tons/acre)	Yield 1100 mg/l (tons/acre)	Price Received ($/ton)	Production Costs[a] ($/acre)	Water Use ($/acre)	Acreage Limits min (acres)	Acreage Limits max (acres)
Alfalfa	7.0 - 9.0	6.0 - 8.9	84[b]	590 - 623	6.3		
Cotton	2.5[c]	2.5[c]	428[d]	949 - 949	5.4		50,000
Wheat	2.6	2.4 - 2.6	134	295 - 295	2.7	50,000	
Sudangrass	5.0 - 5.3	4.5 - 5.3	72	269 - 286	3.2	22,000	35,000
Sugar beets	25.5 - 26.0	25.0 - 26.0	41[e]	693 - 769	6.7-7.1	35,000	50,000
Onions	14.3	13.1 - 13.7	211	3455 - 3673	4.7	4,500	7,500
Tomatoes	10.2 - 11.0	8.8 - 11.0	54	1551 - 1666	7.4	1,500	4,000
Broccoli	2.8 - 3.2	2.2 - 3.2	584	2386 - 2932	4.7	2,500	9,000
Carrots	17.2	15.4	183	3971 - 4301	5.8	4,000	13,000
Lettuce	8.8 - 12.2	5.4 - 11.7	302	1895 - 2885	3.8	30,000	45,000
Cantaloupe	6.1 - 6.8	5.0 - 6.8	338	1662 - 1666	2.5-4.1	10,000	30,000
Watermelons	9.7 - 11.0	8.0 - 11.0	165	1648 - 1741	3.4	2,000	5,000
Asparagus	1.9	1.67	2144	4009 - 4433	5.8	2,000	4,000

1987 dollars
[a] Production cost variation is the result of yield dependent harvest costs and irrigation frequency. Excludes water delivery cost of $9/af.
[b] Does not include $40/acre forage value
[c] Units are bales/acre
[d] Units are $/bale

Total acreage is constrained to 450,000 acres on which 580,000 acres of crops can be grown in a single year; double cropping is thus allowed on 130,000 acres. Two representative soil types are included to model the heterogeneity found in the valley. Loams and sandy loams, and loamy sands are characterized as well-drained soils, while poorly drained soils include silty clays and silty clay loams (Gardner, 1983). There are 140,000 acres of well-drained soils with the balance of 310,000 acres poorly drained. Crops can be grown on each of the two soil types, though higher yields are obtained on well-drained soils. Yield reductions on poorly drained soils can be lessened (or eliminated for some crops) by increasing irrigation applications from the normal 16 per crop to 22 applications. Use of more frequent irrigations is included as a production activity for many crops. This change in irrigation practice is also beneficial in reducing impacts of salinity. The production activities included in the linear programming model are given in Table 3.5.

Returns to Water

Each model is independently solved for varying water levels to obtain net income as a function of water use. Model solutions are similar and the following description applies to both models. Water use reductions of up to 18 percent, or 0.4 maf are possible at very low marginal cost by crop switching out of alfalfa. The actual cost of this very substantial water savings may be somewhat understated by the use of custom rates in alfalfa budgets used to prepare the model. Further low cost reductions in water use of 0.5 maf are possible as both cotton and alfalfa acreage is reduced. Total water savings in excess of 0.9 maf are possible only with reductions in acreage of high value crops. Given the acreage limits in the models, total water savings of up to 1.2 maf are possible, but the last 0.4 maf is achieved at costs of up to $150/af. Figure 3.3 shows

Table 3.5 Cropping activities included in Imperial Valley model.

Crop I	Single Crop	Second Crop for Double-cropping				
		Sudangrass	Broccoli	Lettuce	Carrots	Cantaloupes
Wheat	W,P[a]	W,P	W,P	W,P,F	W	W,P,F
Sudangrass	P[a]		W,P	W,P,F	W	
Tomatoes	W,P,F[a]	W,P,F		W,P,F		
Watermelons	W,P,F[a]	W,P,F		W,P,F		
Cantaloupes	W,P,F[a]			W,P,F		W,P,F
Onions	W	W				
Alfalfa	W,P,F[b]					
Cotton	W,P					
Sugar Beets	W,P[c]					
Asparagus	P					

Key to activities: W - well drained soils, P - poorly drained soils,
F - frequent irrigations (22/crop) on poorly drained soils

[a] Grown as cover crop for alfalfa stand establishment.
[b] Frequent irrigations on well-drained soils included in 1100 mg/l model.
[c] Sprinkler irrigation on poorly drained soils included in both models.

profits as a function of water use for the 800 mg/l and 1100 mg/l salinity models.

Derived (inverse) demand functions p(x) for each model are estimated from profit differences by the function

$$p = a\,(x - x_0)^b \qquad (3.3)$$

where x_0 is taken as the minimum water delivery consistent with the acreage constraints given in Table 3.4. Use of a non-linear functional form is chosen based on the large difference in returns to water in low value (alfalfa and cotton) crops compared to high value crops (Figure 3.4). While a piecewise linear functional form would also be satisfactory for this work, use of a continuous function simplifies incorporation in CRIM.

Net income as a function of water use is obtained by integration of equation (3.3) to give

$$\pi(x) = \pi_0 + \alpha\,(x - x_0)^\beta \qquad (3.4)$$

where $\alpha = a/(b+1) < 0$ and $\beta = b+1 < 0$ and π_0 is the constant of integration. π_0 is determined for each model by setting net income in equation (3.4) equal to the net income at 2.2 maf given in the linear program solutions. Net income as a function of water use estimated directly from each linear programming model, and given by equation (3.4) is shown in Figure 3.4. The functions are given by

$$\pi_{800}(x) = 95 - 370\,(x - x_0)^{-0.43} \qquad (3.5)$$

$$\pi_{1100}(x) = 64 - 520\,(x - x_0)^{-0.59} \qquad (3.6)$$

in 1989 dollars, where x_0 is the minimum allocated water use of 1,220 kaf and net income has units of million dollars.

Since the linear programming models presented here do not include losses from off-farm delivery systems, the minimum water use level must be adjusted upward to account for these losses. The maximum withdrawal at Imperial Dam for use by Imperial Valley irrigators in the period 1982 to 1987 was 2,640 kaf (USBR, 1982-87) in 1987. Identified transport losses of 270 kaf give on-farm deliveries 70 kaf less than the 2,440 kaf maximum use found by the linear programming model. For simplicity, transport losses of 200 kaf are assumed. These losses are incorporated in equations (3.5) and (3.6) above by setting $x_0 = 1{,}100+200=1{,}300$ kaf. This gives net income as a function of Colorado River withdrawals for Imperial Valley agriculture in 1989 dollars.[11]

[11] Water withdrawals and consumptive use for Imperial Valley irrigation are identical since return flows are not used; they flow directly to the saline Salton Sea and are lost to further consumptive use.

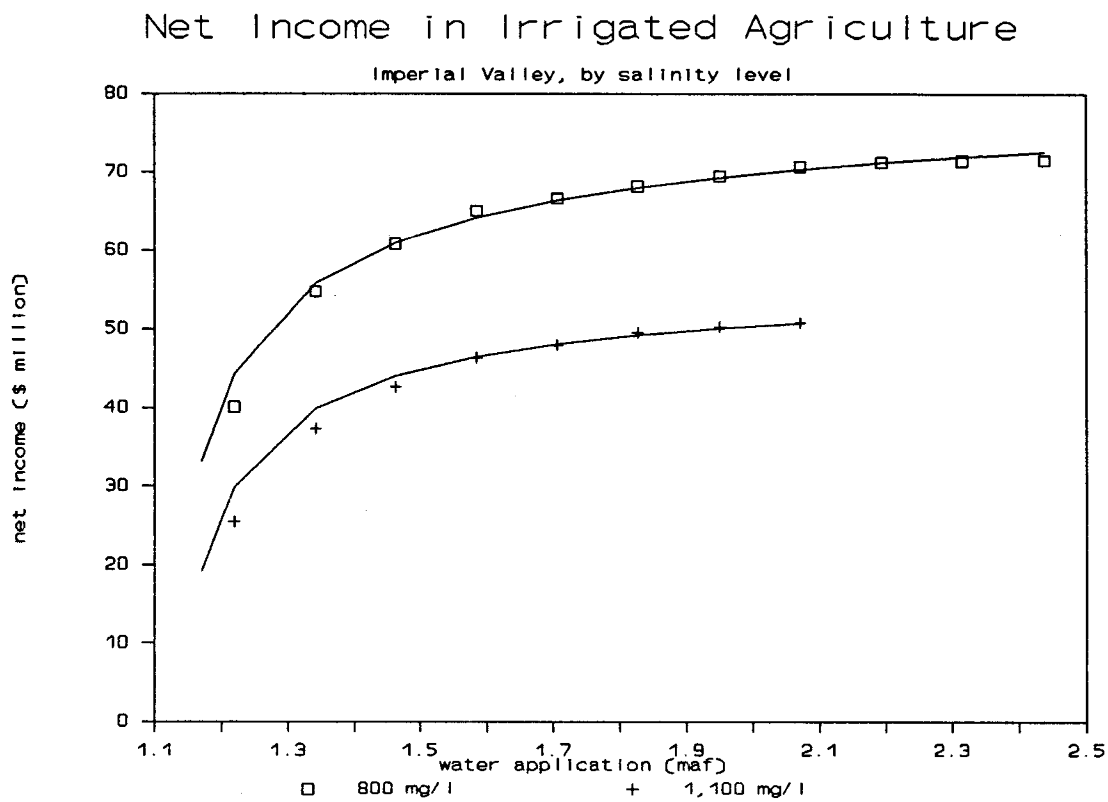

Figure 3.3 Imperial Valley profits as a function of water use, 800 and 1100 mg/l models. (The curve connects the points representing solutions from the linear programming model).

Salinity damages are determined by the difference between π_{800} and π_{1100} at each water use level. If σ is the salinity level of Colorado River water in mg/l then total damages $c(x,\sigma)$ are given by

$$c(x,\sigma) = (\sigma/300)(\pi_{800}(x) - \pi_{1100}(x)) \qquad (3.7)$$

Salinity damages are assumed linear in salinity level, but marginal damages are decreasing in water use x (see Figure 3.3). For full withdrawals of 2,640 kaf, equation (3.5) gives damages of $65,000 per mg/l in 1989 dollars. Using models on which those presented here are based, Gardner found comparable damages of $58,000 per mg/l. Kleinman and Brown (1980) found damages ranging from $7,000 per mg/l at 800 mg/l salinity to $35,000 per mg/l at 1100 mg/l salinity. Moore, Snyder and Sun (1974) reported damages to Imperial Valley irrigators of $43,000 and $67,000 per mg/l in the ranges 480-960 mg/l and 960-1280 mg/l respectively. All figures are adjusted to 1989 price levels using the GNP deflator.

Marginal salinity damages to irrigators appear to increase with salinity. Since the model used here is based on anticipated yield losses at unrealistically high salinity levels of 1100 mg/l, the damage estimates should be considered an upper bound on actual marginal damages sustained at likely salinity levels of 800-900 mg/l.

Future Demand Functions

The 1990, 2010, and 2030 profit functions for use in CRIM are derived from the functions given in equations (3.5) and (3.6). The 1990 profit function is derived directly from the model estimates given in (3.5) and (3.6) by a simple adjustment for returns to water included in land rental costs. The minimum rental cost,

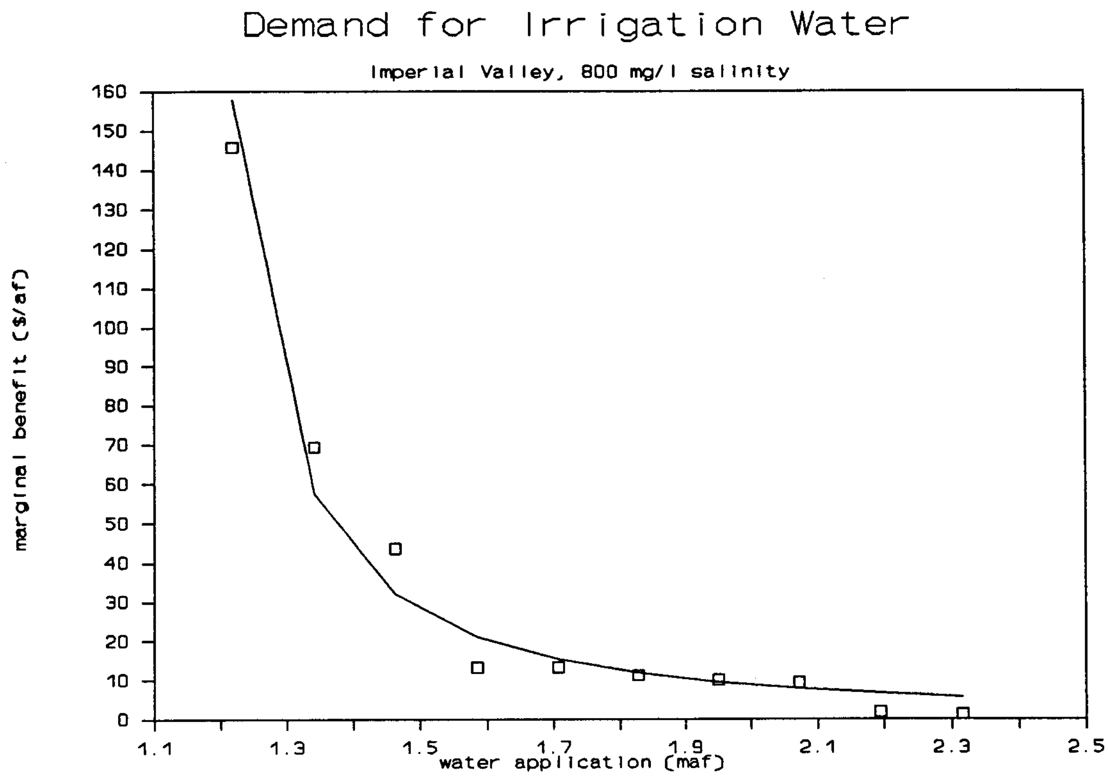

Figure 3.4 Imperial Valley derived demand for irrigation water, 800 mg/l model. (The curve connects the points representing solutions from the linear programming model).

$80/acre, or $12.7/af is subtracted from (3.5) and (3.6) for use in CRIM. Year 2010 and 2030 profit functions used in CRIM include the same land rental cost adjustment, and are assumed to grow at the national population growth rate, estimated at 0.5 percent per year (U.S. Department of Commerce, 1989). Resulting demand functions for Imperial Valley agriculture used in CRIM are given in Table 3.6. The adjustment for water values implicit in land rental costs is not included.

It is anticipated that significant improvements to off-farm delivery systems will be made in the next decade. In particular, the recently completed agreement between the Metropolitan Water District (MWD) and the Imperial Irrigation District is expected to result in savings of 100,000 af (Quinn, 1990). Lining of the All-American canal is projected to save at least an additional 70,000 af. Since any savings resulting from the improvements will be captured by MWD, little effect on the on-farm demand for irrigation water developed in this section is anticipated.

Extrapolation to Additional Agricultural Sectors

The water demand functions determined above for the Imperial Valley and Grand Valley are used as the basis for approximations of water demand in other agricultural sectors. Economic demand specifications for all major agricultural users of basin water are used in the two full basin scenarios modeled by CRIM. Imperial and Grand Valley irrigated agriculture are considered representative of lower and upper basin agriculture, respectively, in estimating these demands. The Imperial Valley supports a large variety of high value crops particularly suited to a near continuous growing season. In addition, it includes substantial acreage

Table 3.6 Estimated Imperial Valley profit functions.

Year	Salinity (mg/l)	Estimated Parameter Values			
		α ($ million/kaf$^\beta$)	β ($ million)	π_0 (kaf)	x_0
1990	800	-367	-0.43	9.5	1,300
	1100	-524	-0.59	6.4	1,300
2010	800	-467	-0.43	10.5	1,420
	1100	-668	-0.59	7.0	1,420
2030	800	-595	-0.43	11.5	1,540
	1100	-851	-0.59	7.8	1,540

1989 dollars
Profit functions are of the form $\pi(x) = \alpha(x - x_0)^\beta + \pi_0$.

in low value crops with returns to water comparable to that seen in upper basin agriculture. The long growing season and very hot summers leads to annual evapotranspiration of up to 6 feet (6 af/acre). The Grand Valley is dominated by corn, alfalfa, and irrigated pasture. This is typical of upper basin agriculture, much of which must cope with harsh winters and relatively short growing seasons.

Extrapolation of the modeled water demands to other agricultural sectors is accomplished by scaling of the respective profit functions based on water withdrawals and depletions reported in USBR (1986b). Two distinct types of adjustment are required. First, a transformation for differences in irrigated acreage between sectors is based on reported consumptive use, or depletions.[12]

Let $\pi_1(x)$ be a known profit function for consumption x by one sector. If sector 2 is equivalent except in scale, then its profit function $\pi_2(x)$ must satisfy

$$\rho\pi_1(x) = \pi_2(\rho x) \qquad (3.8)$$

where $\rho = x_2/x_1$ is the ratio of maximum consumptive use (or acreage) in the two sectors. This transformation is equivalent to a horizontal shift of the demand function.

The simplified profit function (not including salinity) for the Grand Valley,

$$\pi_1(x) = a + bx + cx^2 \qquad (3.9)$$

is used for extensions to other upper basin agricultural sectors. This is equivalent to assuming that upper basin irrigators outside the Grand Valley are not salt producers. Many upper basin regions besides the Grand Valley are in fact significant salt producers. This non-modeled externality should be considered in interpreting CRIM results. In particular, economically efficient levels of water use in upper basin salinity producing regions are overestimated in scenarios including water transfers based in part on the value of lower basin salinity damages.

Using equations (3.8) and (3.9), profits in other upper basin sectors must satisfy

$$\pi_2(x) = \rho a + bx + (c/\rho)x^2 \qquad (3.10)$$

which clearly satisfies (3.8). It is easy to verify that the lower basin profit function for sector 2 is given by

$$\pi_2(x) = \rho\pi_0 + \alpha\rho^{-\beta+1}(x - \rho x_0)^\beta \qquad (3.11)$$

where α, β, and π_0 are constants and x_0 is the minimum use by the first sector.

The scaling of 1990 Grand and Imperial Valley demand functions in modeled sectors to year 2010 and 2030 levels follows this same approach.

[12] It is assumed that the Imperial Valley has 60% consumptive use efficiency; the remainder is lost to the Salton Sea and deep aquifers. Similarly, Coachella Valley return flows are lost to other Colorado River users, and 60% of withdrawals are assumed used for evapotranspiration or beneficial leaching.

A second transformation of profit functions is also required to give profit as a function of withdrawals w as required by CRIM. Let two sectors have irrigation efficiencies η_1 and η_2 respectively. If the two sectors are otherwise identical, then adjustment for the different irrigation efficiencies requires that profit functions $\pi_1(w)$ and $\pi_2(w)$ satisfy $\pi_1(w_1) = \pi_2(w_2)$ for all withdrawals w_1 and w_2 where $w_2=(\eta_1/\eta_2)w_1$. Relationships similar to those in equations (3.10) and (3.11) can be derived in this case. The transformation is equivalent to stretching or shrinking the demand function.

CHAPTER 4
WATER FOR USE IN ENERGY PRODUCTION

Water is used in the Colorado River basin to produce hydroelectric power, and for cooling in thermal energy technologies. The latter use is dominated by the use of cooling water in coal-fired electric generating plants. The first use is an instream, nonconsumptive use, while the second use is typically an offstream consumptive use. Economic demand for basin water by the two sectors is developed below.

Hydropower Valuation and Production

Electric power generation from Colorado River hydroelectric plants produces significant economic value. The combined head of the mainstem dams at and below Glen Canyon is over 1,100 feet (Gibbons, 1986), with significant additional head at upstream mainstem and tributary dams. Total basin hydropower production averages 1,200 kilowatt-hours (kwh) per acre-foot delivered to the lower basin at Lee's Ferry (USBR, 1986c). Electricity from upper basin power generation (primarily at Glen Canyon) is used in all basin states. Lower basin generation (mostly at Hoover dam) is supplied to customers in Arizona, Nevada, and California. The largest single customer is MWD, which consumes about 1.6×10^9 kwh annually (MWD, 1988) to pump Colorado River water through the Colorado River Aqueduct to the southern California coast.

Economic Value of Hydropower Production

The economic value of Colorado River hydropower cannot be estimated by investigating terms of basin hydropower sales. Most firm energy sales are fixed by long term contracts with the Department of Interior at highly favorable rates. An appropriate measure of economic value is the cost avoided by utilities in substituting hydropower for the best available alternative (Munasinghe and Warford, 1982). This opportunity cost is measured in the short run by the operation and maintenance costs of alternative electrical generation capacity, minus the operation and maintenance costs of hydropower generation. An additional penalty (or premium) is necessary if significant differences in transmission costs are incurred. If excess capacity does not exist in the future, then capital costs of constructing additional generation capacity must also be added. In this case, increasing the firm yield from hydropower supplies would be particularly beneficial. Such strategies are discussed for the Snake River basin in southern Idaho by Hamilton, Whittlesey, and Halverson (1989). For this research, capital costs of alternative generation capacity are not considered, though this approach almost certainly underestimates future values of basin hydropower production.

Tables 4.1 and 4.2 summarize most existing generation capacity in the lower and upper basins, respectively (U.S. Department of Energy, 1988a). Capacity factors (proportion of time the plant was generating electricity) and operation and maintenance costs for 1986 are given. The most costly plants to operate tend to have the lowest capacity factors, indicating that (desirably) the least costly plants are used at the margin. Avoided cost in using hydropower for this study is defined as the capacity-weighted average of the most costly 50 percent of total capacity, calculated separately for upper and lower basin states. While it could be argued that the most costly utilized plant gives the avoided cost, at periods of low use less costly plants almost certainly generate the marginal power. The use of a broad average also addresses operational constraints imposed by transmission line capacity and other factors. The disposition of power from upper and lower basin hydropower plants is used to calculate avoided costs by state.

Calculation of economic benefits from use of basin water for hydropower generation also includes operation and maintenance costs at hydropower plants, plus differences in transmission costs from hydropower sites and alternative sources to demand centers. Following Abbey (1979), transmission costs of 2.1 mills/kwh/100 miles (1989 dollars) are used. Alternative costs are weighted by the proportion of power serving upper and lower basins. Table 4.3 shows the benefit calculation for 1990 upper and lower basin hydropower production. Using this approach, avoided costs are 44.2 and 26.0 mills/kwh in lower and upper basins, respectively.

Table 4.1. Lower basin electric generation plants.

State	Plant	Rating (MW)	Capacity Factor (%)	O&M Cost (mills/kwh)	First Year
Arizona	Springerville	420	23	68	1985
	San Tan	414	22	40.1	1974
	Navajo	2409	75	14.4	1976
	Cholla	1105	32	23.8	1962
	Coronado	822	59	32.4	1980
	Palo Verde	2719	38	22.6	1986
	Yucca[a]	192		63	1971
	Saguaro[a]	106		73	1972
	Phoenix[a]	106		74	1972
	Ocotillo[a]	106		59	1972
California	ElSegundo	996	23	37.4	1955
	Alamitos	2120	24	35.4	1956
	Long Beach	586	20	36.6	1928
	Huntington Be	1008	14	37.8	1958
	Morro Bay	1056	21	51.3	1955
	Encina	982	24	37.7	1953
	Moss Landing	2175	23	40.7	1950
	Redondo Beach	1580	29	32.4	1948
	Pittsburg	2029	25	40.6	1954
	South Bay	714	29	36.9	1960
	Contra Costa	1291	16	42.5	1951
	Etiwanda	1049	15	38.1	1955
	Ormand Beach	1613	21	38.2	1971
	San Onofre[b]	2710	58	35.6	1968
	Diablo Canyon[b]	2376	59	19.8	1985
Nevada	Mohave	1636	66	19.8	1971
	Reid Gardner	636	50	41.3	1965
	Sunrise	82	18	40.6	1964
	Clark[a]	420		60.7	1973

Source: U.S. Department of Energy (1988a)
1986 dollars
Unless noted, all plants are fossil fueled steam plants.
[a] Gasturbine plant
[b] Nuclear plant

Table 4.2. Upper basin fossil fueled steam electric generation plants.

State	Plant	Rating (MW)	Capacity Factor (%)	First O&M Cost (mills/kwh)	Year
Utah	Hunter (Emery)	1339	45	19.4	1978
	Huntington	893	58	19.5	1974
Wyoming	Dave Johnston	750	62	14.6	1959
	Jim Bridger	2034	51	17.8	1974
	Wyodak	332	69	20.8	1978
	Naughton	707	46	20.8	1963
Colorado	Rawhide	255	79	16.6	1984
	Cherokee	804	46	19.1	1957
	Comanche	779	50	18.4	1973
	Pawnee	552	74	16.8	1981
New Mexico	Four Corners	2270	61	17.6	1963
	San Juan	1779	61	23.4	1973
	Cunningham	265	43	39.1	1957

Source: U.S. Department of Energy (1988a)
1986 dollars

Table 4.3. Calculation of net benefits to hydropower, upper and lower basins.

State	Avoided Cost	Disposition of Hydropower		Additional Transmission Cost[a]	Weighted Net Benefit	
	(mills/kwh)	Upper (%)	Lower (%)	(mills/kwh)	Upper (mills/kwh)	Lower
Calif.	47.8	1	65	2.9	0.40	28.30
Arizona	47.8	15	18	2.9	6.60	7.69
Nevada	47.8	6	18	0.0	3.03	8.19
Colorado	24.4	27		2.3	5.57	
Utah	24.4	28		4.3	5.37	
Wyoming	24.4	10		0.0	2.38	
N.M.	24.4	12		1.4	2.61	
Totals	100	100			26.0	44.2

1989 dollars
Total net benefits are the sum of the weighted net benefits; disposition of hydropower gives the allocation by state under present contracts.
[a]Based on costs of 2.1 mills/kwh/100 miles (Abbey, 1979).

Hydropower Production

Energy production estimates from basin dams are derived below based on estimates used by the Colorado River Simulation Model (CRSM), developed by the USBR (1986a). The results of one study (USBR, 1986c) using this model provides average annual upper and lower basin energy production and releases from Glen Canyon and Hoover dams for a variety of average annual flows. Linear functional forms fitted to these release and hydropower production levels were very successful in explaining both upper and lower basin hydropower generation. Estimated coefficients are used in CRIM to give power production as a function of river flows leaving the hydropower nodes.

Figure 4.1 shows energy production as a function of Glen Canyon and Hoover Dam releases and ordinary least squares linear estimates of hydropower production. While reservoir levels influence power production and are considered in CRSM, the effect is small compared to other factors. In Figure 4.1 the linear estimates do not systematically overestimate power production for low flows, and hence low reservoir levels.

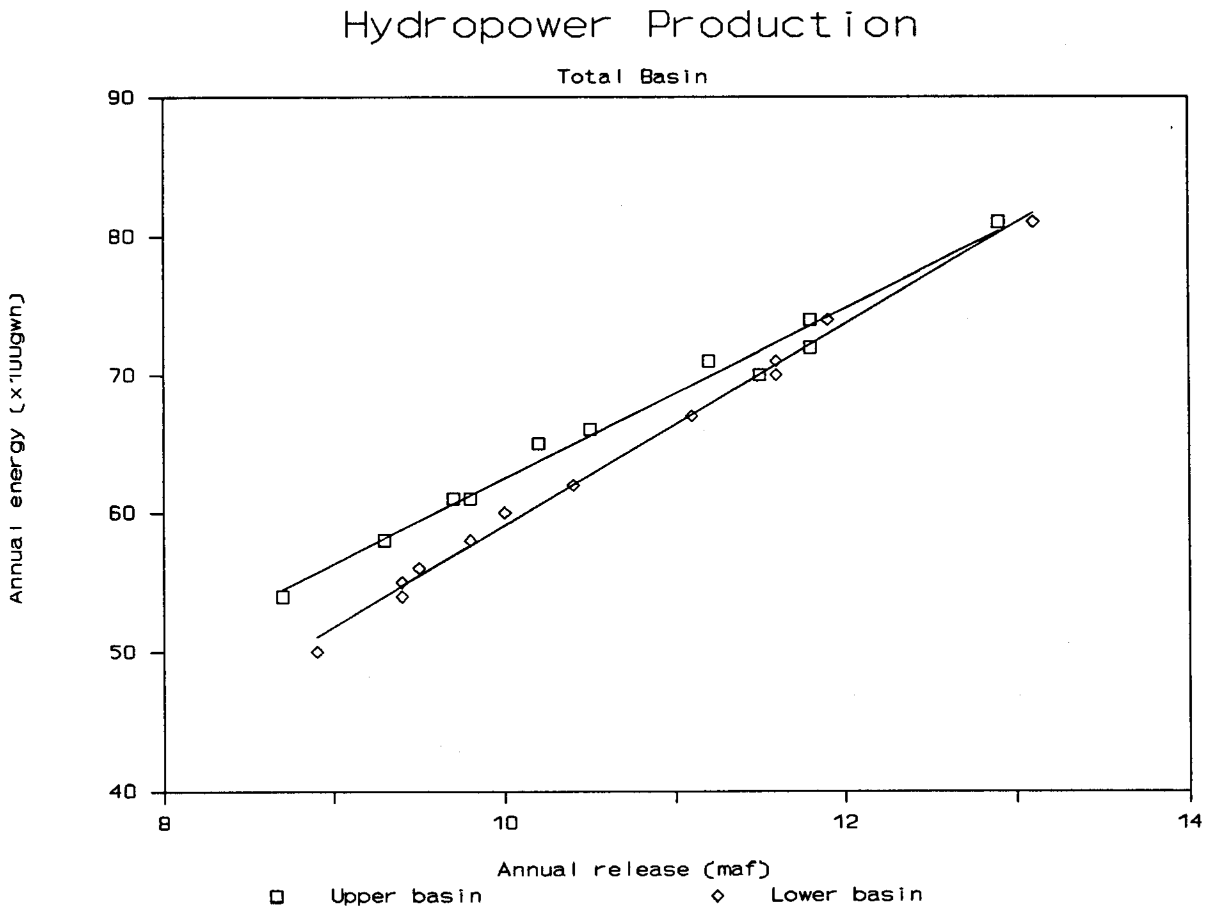

Figure 4.1. **Upper and lower basin hydropower generation as a function of average annual releases from Glen Canyon and Hoover dams.**

Using these estimates, upper basin energy production is given by

$$E_U = 93 + 0.616\, Q_U \qquad (R^2=0.99) \tag{4.1}$$

where E_U is energy production in million kwh (gwh), and Q_U is the total volume released from Glen Canyon dam in kaf. Lower basin production (using the same units) is

$$E_L = -14 + 0.724\, Q_L \qquad (R^2=0.99) \tag{4.2}$$

where Q_L is the volume released from Hoover dam.

Water Use in Thermal Energy Production

Colorado River water is an important source of cooling water for coal fired electric generation. Much of the generation capacity shown in Table 4.2 above relies on basin water. This section will examine in detail the economic demand for cooling water by coal-fired electric generating plants, the dominant basin consumptive use of water for energy production. Estimates for economic demand for water in coal gasification plants will also be presented. Coal liquefaction and oil shale production are additional technologies which will be discussed.

Development of economic demand functions for cooling water is based on the cost of alternative cooling technologies. Recycling of cooling water (number of cycles of concentration of blowdown water) and disposal methods are assumed constant across technologies. Condensation and cooling of process steam is possible using once-through cooling, cooling ponds, wet tower cooling, dry tower cooling, or hybrid wet/dry cooling towers. Once-through systems are not considered because of large required diversions and subsequent water temperature increases. Cooling ponds have unacceptably high consumptive use and are not generally considered for use in the arid West. The typical technology, in use by almost all large steam-electric plants in the basin, is wet cooling towers. Evaporation from these cooling towers is the dominant consumptive use in energy production in the basin. This situation is unlikely to change in the future, even with possible development of synthetic fuel and oil shale technologies.

Steam Electric Generation

Dry cooling and hybrid wet/dry cooling systems have been proposed to dramatically reduce consumptive water use requirements. These capital intensive systems can range from very to moderately costly relative to total electric generation costs. Use of hybrid systems is generally much preferred, particularly during summer days when high ambient temperatures limit dry cooling to 140° F thus reducing plant conversion efficiency. Resulting losses in energy production are a cost of employing dry cooling and are valued by the cost of additional summer generation capacity. Total dry cooling would cost 16 mills/kwh, while a wet/dry system reducing cooling water consumption by two-thirds would add only 3 mills/kwh to generation costs (Gold and Goldstein, 1979, and Abbey, 1979). The Wyodak 320 MW plant in Gillette, Wyoming employs only dry cooling. No hybrid plants are known. Estimates of breakeven water costs for adoption of hybrid cooling systems in coal fired steam-electric plants, and total water requirements, are shown in Figure 4.2.

Synthetic Fuels and Oil Shale

Water requirements for synthetic fuel and oil shale production are also dominated by cooling water needs. Again, hybrid wet/dry cooling systems appear to be the most cost effective conservation techniques. Cost estimates by Gold and Goldstein (1979) indicate that use of hybrid systems to achieve a one third reduction in total water needs in a Lurgi coal gasification plant is optimal at water costs above $80/af. Coal liquefaction and oil shale production have similar cooling needs. While cost estimates for conservation measures with these technologies are not available, they are believed similar to those obtained for coal gasification.

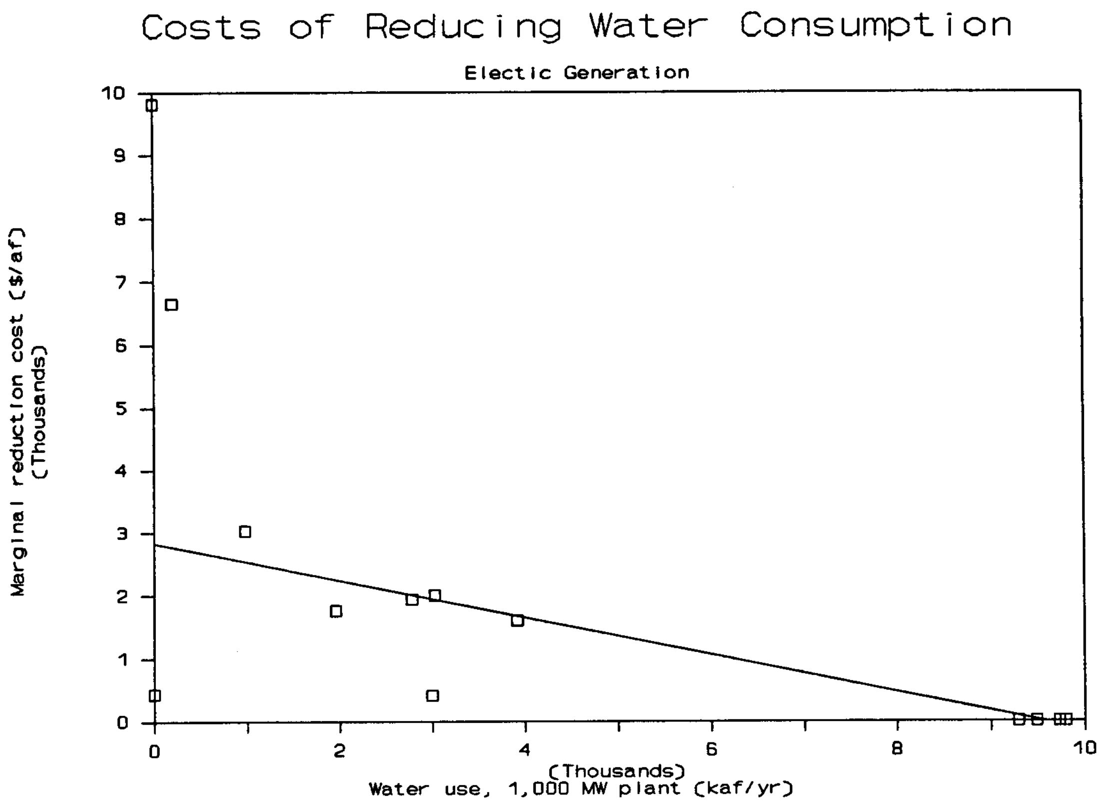

Figure 4.2. **Estimation of demand for cooling water.**

<u>Water Treatment and Salinity Impacts</u>

Salinity control efforts in the basin have generally resulted in a zero discharge policy from energy producing plants. This policy will not be considered in this study, though it is suspected that it represents a very costly salinity control measure. Disposal costs under this policy are dominated by costs of evaporating residual water not recycled for further cooling uses. It is assumed that the same level of final concentration is achieved in all wet cooling uses; water disposal costs are thus a function of the proportion of wet to dry cooling at a particular site. Because water disposal costs decrease as dry cooling increases, the actual cost of using wet/dry cooling technologies is decreased by the difference in disposal costs. Full recycling using 3-stage electrodialysis appears to be the most cost-effective technology, costing from $190 to $290 per af of water evaporated for cooling (Gold and Goldstein, 1979). If recycling to extinction is not possible and evaporation ponds are employed, costs of waste water disposal are $1,000 -$2,000/af (Abbey, 1979, and Gold and Goldstein). The quantity of waste water actually generated depends on the level of recirculation and the recovery level of water from solid waste streams. Use of dry or almost dry cooling could be significantly more attractive if site-specific water quality factors dictate limits on in-plant water recycling.

If zero discharge policies are enforced, then salinity impacts result only from loss of dilution water. Further, it is generally believed that salinity impacts from return flows from disturbed land are small compared to impacts of lost dilution water (Ballard and Devine, 1982). In this case withdrawals for use in energy production are effectively salinity exports from the basin. For this study, salinity impacts from water use in energy production are limited to dilution effects.

Water Demand Functions for Energy Production

The water demand function is based on avoided costs of all-wet cooling systems in coal-fired electric generating plants. Figure 4.2 shows estimates from Gold and Goldstein, 1979, Abbey, 1979, and the U.S. Department of Energy (1983). The linear fit is obtained by neglecting the latter source (avoided cost is questionably low), and the all-dry and 2 percent wet cooling options given by Abbey. To properly include the high costs of going to all dry systems use of a nonlinear function would be appropriate. Because such systems are unlikely to be required[13] they are excluded from the analysis by the choice of functional form.

The total demand function is derived from estimated avoided costs. Adjustment for reduced treatment and disposal costs with wet/dry cooling systems should in principle be made. Based on Gold and Goldstein's estimate of treatment costs of 0.24 mills/kwh, cost savings in moving to hybrid cooling systems are $140/af for wet systems. Given uncertainties in the treatment and disposal costs this potential cost savings is neglected in this work.

Total water requirements for wet cooling systems are derived from USBR (1986a) estimates of water requirements for thermal power generation, and coal gasification and oil shale projects. If Q_r is the water requirement given wet cooling, then the demand function is given by

$$P = 2830 - (2830/Q_r)Q \qquad (4.3)$$

The economic demand sector for present energy production considered in this study is given by estimates of 1990 water requirements for thermal energy production in the Yampa River reach (USBR, 1986b). Demand for cooling water for coal gasification and oil shale production is presently negligible.

Future Demand

Forecasting future water demand for basin energy production is highly speculative. Most projections of energy development in the basin made in the 1970's spectacularly overestimated the present level of development (see, for example U.S. Department of Interior, 1974 and Denver Research Institute, 1981.) World petroleum prices are a major factor in driving basin development, but are difficult to predict. The recent Iraqi invasion of Kuwait and resulting petroleum price rises serves to underscore the volatility of energy prices. Further, multiplier effects of basin energy development would likely impact upper basin population growth. The cost of alternative energy technologies are highly uncertain. While some estimates suggest that oil shale could become economically promising at petroleum prices of $30/barrel (Leibson, 1987), recent experience at the Unocal demonstration plant in western Colorado indicates that breakeven costs may be much higher (Fortune, 1988). The costs of mitigating environmental impacts are also difficult to estimate. In addition to impacts of large-scale surface mining, concern about the relatively high carbon content of coal-based fuels[14] may significantly retard development of coal-based electric power (Rubin, 1989).

Given the above uncertainties, growth in water demand for fossil fuel based energy production is expected to result largely from incremental increases in coal fired electrical generation capacity. Planned capacity increases to the year 1998 are based on utility-reported construction plans (U.S. Department of Energy, 1988b), and are relatively reliable. Capacity increases to 2010 consider projected increases in consumption of electrical energy in all western states (U.S. Department of Energy, 1990a) and are given in Table 4.4. The national forecast, of which this is one component, agrees closely with a number of additional forecasts (U.S. Department of Energy, 1990b). Projections for 2030 rely both on 1990-2010 annual growth rates, and on projections implicit in the CRSM demand data projections (USBR, 1986b). CRSM projections are given in Table 4.5. Because of the similar forecasts in total growth, those implicit in the CRSM demand set are used for this study.

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[13] Use of saline groundwater is probably less costly than going to all-dry systems. In any case, shadow prices in model solutions do not approach the very high unit costs of all-dry systems.

[14] Fossil fuels with high carbon to hydrogen ratios lead to the highest carbon dioxide emissions which may lead to global greenhouse warming.

Table 4.4. Growth projections and growth rates for electric energy consumption.

Federal Region	1989	1995	2000	2005	2010	Average Annual Growth
FR8	82.5	101.6	115.2	127.8	141.5	
		3.5%	2.5%	2.1%	2.1%	2.6%
FR9	267.6	333.8	386.5	435.4	488.2	
		3.8%	3.0%	2.4%	2.3%	2.9%
FR10	151.3	180.1	204.3	226.3	248.6	
		2.9%	2.6%	2.1%	1.9%	2.4%
Total	501.4	615.5	706.0	789.5	878.3	
		3.5%	2.8%	2.3%	2.2%	2.7%

Source: U.S. Department of Energy (1990a).
Energy consumption figures are in gwh/year.
FR8 includes Montana, North and South Dakota, Wyoming, Utah, and Nevada.
FR9 includes California, Nevada, Arizona, and Hawaii.
FR10 includes Washington, Oregon, Idaho, and Alaska.

Table 4.5. Estimated water requirements for thermal-electric generation facilities, by state, and other energy producing plants.

State	1990	2010	2030
Arizona	22	22	22
Nevada	18	0	0
Colorado	17	64	67
Utah	37	49	79
Wyoming	41	41	41
New Mexico	121	121	121
Sub-total	256	297	330
Growth rate	0.7%	0.5%	0.6%
Gas & oil shale	0	106	220
Total energy needs	256	403	550
Growth rate	2.3%	1.6%	1.9%

Source: USBR (1986b)
All figures are in kaf/year.

Development of new electrical generation capacity is assumed in the Yampa River drainage. This is consistent with projections of future construction of additional power plant capacity in the Craig-Hayden area. Limited development of oil shale is assumed in the Piceance Basin in Colorado, utilizing White River water. The greatest concentration of world oil shale deposits is located in the Piceance Basin (Taylor, 1987) in addition to the only U.S. oil shale demonstration project. Coal gasification or liquefaction projects are included in projected increases in fossil fuel generation drawing from Yampa River water. Table 4.6 gives both present (1990) and projected demand functions for water in energy production in the Yampa and White River sectors.

Table 4.6. **Water requests and demand functions for energy production, Yampa and White River demand sectors.**

Demand sector	Use	1990	2010	2030
Yampa River	thermal electric	13	55	55
	coal gasification		15	15
White River	oil shale		20	68
Total	all energy production	13	90	138
Demand function coefficients				
	a	2830	2830	2830
	b	-218	-31.4	-20.5

Request levels from USBR (1986b)
1989 dollars
Demand functions are of the form P=a+bQ, where Q is in kaf and P has units of $/af.

CHAPTER 5
SOUTHERN CALIFORNIA MUNICIPAL WATER DEMAND

The Colorado River is the largest single source of water for southern California municipal uses, providing supplies for almost one third of the total area consumption. Up to 1.3 million acre-feet (maf) can be delivered annually to the coastal metropolitan areas, with typical annual deliveries in excess of 1 maf. Colorado River water is diverted at Lake Havasu and pumped to the municipal region through the Colorado River Aqueduct.

Development of economic demand functions for southern California municipal use of Colorado River water requires several steps. First, econometric estimates of household water demand functions are made using monthly consumption data for 21 southern California communities provided by regional water utilities and compiled by Walters and Young (1990). Total municipal area water demand for municipal water is then developed from the estimated household demand function, the 1985 regional average marginal price for household water, and estimates of 1985 metropolitan area water use. Demand for Colorado River water is found by assuming that alternative supplies are inframarginal sources and are available and used at 1985 levels in all years. Colorado River water is then the marginal supply source, and economic demand for raw water is found by subtracting conveyance and treatment costs for water diverted at Lake Havasu.

Household Water Demand Estimation

Household water demand is estimated using a simple linear model of household water use. Community level data on single family residence water use, average bills, rate structures, and several additional factors are used to estimate model coefficients. Water and electricity demand models have often included an unnecessary variable which greatly complicates model estimation; the discussion below addresses this problem and presents the household demand model chosen for use in development of municipal level water demand functions for this study.

Water Demand Models

Recent work on residential utility demand has concentrated on the problem of simultaneity under non-uniform pricing structures. Typical water tariffs include a service charge plus increasing or decreasing block rates based on consumption. The actual (ex post) marginal and average price paid by consumers is a function of quantity consumed. Single equation estimates of coefficients on price variable may therefore be biased. An additional concern is the income effect introduced by non-uniform pricing. It has been common to introduce an income difference variable defined as the difference between the actual water bill and the total cost had the (observed) marginal price been charged for all water used. It is argued below that in addition to introducing an additional source of simultaneity bias, use of the income difference variable causes misspecification bias and is unnecessary. Model estimates from the data set used here support this conclusion.

The Role of Income Effects

Recent studies of household water demand have typically included an income difference variable D to incorporate income effects of non-uniform rate structures. Taylor (1975) notes the complexities introduced into electricity demand models by block rate pricing using utility maximization theory. He suggests the use of both marginal and average price variables as a suitable specification. Nordin (1976) shows that for consumption within a single marginal price block a possible specification includes marginal price plus an income difference variable D to compensate for the consumer surplus change caused by non-uniform pricing. The typical specification using Nordin's approach is then

$$Q = f(p_m, D, M, X) \qquad (5.1)$$

where Q is household water consumption, p_m is marginal price, and X is a vector of other explanatory variables.

Income difference D is defined by

$$D = (p_a - p_m)\,Q \qquad (5.2)$$

the difference between the actual bill and that which would result from a constant rate. Q is the quantity used and p_a and p_m are average and marginal price, respectively, paid by the consumer. Because D measures a lump-sum income change, theory predicts $\partial Q/\partial D = -\partial Q/\partial M$, where M is income. Since household potable water is a normal good, the standard hypothesis is $\partial Q/\partial D<0$ for well-informed utility maximizing consumers.

It is instructive to consider the theoretical role of D in a demand model. Suppose D is negative, implying an increasing block rate structure. If the total water bill were zero (possible in principle with a negative service charge), then excluding D would result in estimation of a compensated demand function. For a positive bill, excluding D would give an estimate bounded by the ordinary and compensated demand functions. Willig (1976) has shown that when expenditures are much less than income, consumer surplus measured using ordinary demand is an excellent approximation of compensating variation. Similar arguments hold when D>0. Error from omission of D in the demand model specification is thus expected to be negligible. Since D<<M (and also because D is much less than the measurement error in income) theory predicts that demand model estimates for $\partial Q/\partial D$ should be insignificant.

Review of Previous Work

Econometric estimates of water demand incorporating distinct explanatory variables D and M tend to reject the hypothesis that $\partial Q/\partial D = -\partial Q/\partial M$. Previous water demand studies using income difference D are summarized in Table 5.1. In particular, the ratio of coefficient estimates of D and M, $(\partial Q/\partial D)/(\partial Q/\partial M)$ is given in the Table, informally showing rejection of the income difference hypothesis $\partial Q/\partial D = -\partial Q/\partial M$. For a more complete, though now somewhat dated review of municipal water demand studies, see Boland, et al. (1984).

Table 5.1. Summary of previous residential water demand studies using income difference variable D.

Data Set	Type	Rate Structure	Estimation Method	Ratio[a] β_D/β_M	Reference
Denton, TX	household time-series	decr,D>0	OLS IV,2SLS	3000 660-900	Nieswiadomy and Nordin
		incr,D>0	OLS IV,2SLS	-650 460-400	
rural Illinois	household time-series	decr,D>0	OLS,IV 2SLS,3SLS,IV	β_D insig 700-1300	Chicoine, Deller, and Ramamurthy
U.S. (Foster & Beattie)	aggregate	mostly decr	OLS[b]	positive	Foster and Beattie (1981)
Tucson	household time-series	incr,D>0	OLS,3SLS	-70	Agthe, Billings, Dobra, and Raffiee
Denver	household cross-section	mixed	IV	-100	Jones and Morris
U.S.(Howe & Linaweaver)	aggregate	decr,D>0	OLS, winter summer (east) summer (west)	-35 -35 90	Howe
Wisconsin	aggregate	OLS[c]	β_D insig		Schefter and David

[a] β_D/β_M is the ratio of coefficient estimates of D and M, in linear models, given by $(\partial Q/\partial D)/(\partial Q/\partial M)$.
[b] Did not report linear functional form estimates.
[c] Used actual rate structure

Failure of the hypothesis is consistent with findings derived from three data sets presented in the Table 5.1. Studies using household data on rural Illinois water users (Chicoine, Deller, and Ramamurthy, 1986, and Deller, Chicoine, and Ramamurthy, 1986), household data from Denton, Texas (Nieswiadomy and Molina, 1989) and aggregate data covering most United States urban areas (Foster and Beattie, 1981) show $\partial Q/\partial D$ large and significant.

Studies using household data from Tucson (Agthe, Billings, Dobra, and Raffiee, 1986) and Denver (Jones and Morris, 1984) give $\partial Q/\partial D$ large in magnitude, but negative. A second aggregate United States data set used by Howe (1982) gives mixed signs by region and season.

One study by Schefter and David (1985) using aggregate data from Wisconsin gives insignificant coefficient estimates for D. Their demand function estimates were based only on rate schedules and did not require ex post calculation of price from consumption levels.

Explanations for failure of the hypothesis $\partial Q/\partial D \approx 0$ have been twofold. One explanation is based on the simultaneity introduced by use of D in single equation demand models. It is clear from equation (5.2) that D and the disturbance term in a single equation model are not independent. This is dealt with in the literature using both instrumental variable and simultaneous equation techniques. It is now well accepted that such approaches are necessary when D is included in the demand model specification. Such procedures may also be necessary with price variables p_a and p_m since both are also functions of water use Q. In particular, p_a is a continuous function of Q given the pricing structure. Of perhaps less concern in most cases, p_m varies with Q only at rate boundaries. It is not the purpose here to investigate the approaches to these simultaneity concerns, but to consider other possible reasons for failure of the hypothesis.

It has also been suggested that consumers are either poorly informed or do not maximize utility with respect to water consumption. While a distinct possibility, especially given the small size of water expenditures, the general argument does not explain the large magnitude for $\partial Q/\partial D$ found in many studies.

An important conclusion of this survey is to confirm that the magnitude and sign of D remains unexplained by the Taylor-Nordin analysis. The puzzle and mystery is to interpret the explanatory power of D found in the studies cited above. A provisional answer is that D is a proxy for consumer response to some part of the rate structure. Model misspecification has been suggested (Deller, Chicoine, and Ramamurthy) but not investigated. Intuitively, D may serve as a proxy for a highly correlated variable omitted from the usual specification. Such a finding would have significant implications for estimation of price elasticities, since demand model misspecification could bias estimates of price coefficients.

The Data Set

The models presented below are estimated using cross-sectional data on total water use in single family residences in 21 southern California communities for 1985. Local water utilities provided information on water use, rate structures, typical bills and billing periods, voluntary conservation programs, and other factors in response to a mailed questionnaire. The 21 communities used here are located in southern California but are taken from a sample of responses from utilities serving communities throughout the Western United States. Details of the survey are given by Walters and Young (1990). Responses from individual utilities were compiled into a single database for this analysis by Walters.

Average household water use for each community is calculated from total system use and the number of connected households. Marginal and average prices, and total water bills are calculated at the average use level for each community from rate structures given in questionnaire responses. Household income is obtained from 1980 U.S. Census figures, adjusted to 1985 levels.

Price structure of surveyed utilities are increasing or decreasing block, or flat rate, but only communities with $p_a > p_m$ are included in the 21 community sample. The presence of service charges with otherwise increasing block rates allows $p_a > p_m$. This restriction on the sample requires D>0 and a price difference variable $p_d = p_a - p_m > 0$. A summary of the data is presented in Table 5.2.

Table 5.2. Summary statistics for household water demand data set.

	Mean	Standard Deviation	Max	Min
Monthly consumption Q (1000gal.)	21.0	7.7	43.2	11.1
Marginal price p_m (\$/1000gal.)	0.84	0.35	1.43	0.00
Average price p_a (\$/1000gal.)	1.16	0.38	2.15	0.60
Price difference p_d (\$/1000gal.)	0.32	0.28	1.14	0.10
Monthly service charge F (\$)	7.63	8.33	41.1	2.00
Annual income difference D (\$1000)	0.086	0.087	0.076	0.052
Annual income M (\$1000)	39.0	22.1	110	18.2
Conservation program dummy C	0.81	-	1	0

1985 dollars

Water Demand Models

Three simple models of consumer water demand are presented to give insight into the unexplained role of D in recent work. Results imply a further mystery and a possible explanation. Linear models are used for comparison with previous work; no judgement on the appropriateness of the functional form is implied.

The models, labelled I, II, and III, respectively, are

$$\text{I.} \quad Q = \beta_0 + \beta_m p_m + \beta_d p_d + \beta_M M + \beta_c C \tag{5.3}$$

$$\text{II.} \quad Q = \beta_0 + \beta_m p_m + \beta_D D + \beta_M M + \beta_c C \tag{5.4}$$

$$\text{III.} \quad Q = \beta_0 + \beta_m p_m + \beta_F F + \beta_M M + \beta_c C \tag{5.5}$$

where M is income, C is a dummy (0,1) variable for existence of a water conservation program in the community, and F is a fixed service charge to receive water. Each model specification includes marginal price p_m.

Model I includes the price difference variable p_d (defined as the difference between average and marginal price) suggested by Opaluch (1982); its use is suggested by the definition of the income difference variable in equation (5.2). In a linear model, including marginal price and price difference variables is equivalent to using marginal and average price variables as suggested by Taylor. In the form given here, if consumers respond to average price then $\beta_m=0$ and $\beta_d<0$. Alternatively, if consumers make decisions at the margin, then $\beta_m<0$ and $\beta_d=0$. Real consumers might respond to both, giving $\beta_m<0$ and $\beta_d<0$.

Model II substitutes the income difference variable D for p_d. The form is typical of the demand models used in the previous work discussed above and summarized in Table 5.1.

Model III differs from I and II only in the substitution of the service charge F in equation (5.5) in place of the price difference p_d in (5.3) and income difference D in (5.4). A possible interpretation of estimates of the three models is presented using Model III and the high correlation coefficients between the variables p_d, D, and F ($\rho_{Fpd}=0.82$, $\rho_{Dpd}=0.94$, and $\rho_{FD}=0.91$.) In particular, it is argued that model results are most easily interpreted in terms of the service charges used in Model III.

Climate variables (monthly maximum and average temperatures, and average rainfall) were found to be insignificant and are not included in the model specifications. Similarly, a proxy for household size, population per water connection, had little explanatory power and is excluded.

Because p_m, p_d, and D are jointly determined with Q, the model specifications given above include simultaneous equations

$$p_m = \alpha_{10} + \alpha_{11}D_1 + \alpha_{12}D_2 + \alpha_{13}D_3 \qquad + \alpha_{15}Q \tag{5.6}$$

$$p_d = \alpha_{20} + \alpha_{21}D_1 + \alpha_{22}D_2 + \alpha_{23}D_3 + \alpha_{24}F + \alpha_{25}Q \tag{5.7}$$

$$D = \alpha_{30} + \alpha_{31}D_1 + \alpha_{32}D_2 + \alpha_{33}D_3 + \alpha_{34}F + \alpha_{35}Q \tag{5.8}$$

A simultaneous equation approach is included here as advocated by Chicoine, Deller and Ramamurthy, Howe, Nieswiadomy and Molina, and Jones and Morris. Following Agthe et al. (1986), dummy variables are used as proxies for changes in rate structure between observations. Because data on actual rate structures were unavailable, the vectors D_1, D_2, and D_3 in equations (5.6) - (5.8) are constructed by grouping actual marginal prices at the average consumption levels into four levels, from lowest to highest. If the first observation had a very low marginal price, then the first element of vectors D_1 - D_3 would be 1, 0, and 0, respectively.

Model Estimation

The models are estimated using ordinary least squares (OLS) and three stage least squares (3SLS). Parameter estimates are presented in Table 5.3. The simultaneous 3SLS estimates of p_m, p_d, and D are given in Table 5.4. Little information is lost in the estimates of p_m or D. Variation in p_d is explained less well.

Table 5.3. Parameter estimates for municipal demand models, equations (5.3) - (5.5).

	Coefficient Estimates					
	Model I		Model II		Model III	
Variable	OLS	3SLS	OLS	3SLS	OLS	3SLS
constant	22.8 (4.4)	18.6 (3.8)	20.4 (4.4)	18.2 (4.5)	20.9 (4.9)	20.2 (5.4)
p_m	-6.8 (1.8)	-4.2 (1.1)	-3.7 (1.0)	-1.7 (0.5)	-3.7 (1.0)	-3.1 (1.0)
p_d	7.6 (1.6)	18.0 (3.4)				
D			32.1 (2.7)	48.0 (4.2)		
F					0.44 (3.1)	0.54 (4.4)
M	0.165 (2.7)	0.157 (3.1)	0.162 (3.0)	0.145 (3.3)	0.161 (3.2)	0.145 (3.3)
C	-6.0 (1.7)	-7.2 (2.6)	-6.6 (2.1)	-6.9 (2.8)	-7.9 (2.6)	-7.8 (3.0)
R^2	0.603	0.473	0.682	0.640	0.709	0.695

Absolute values of t-statistics are in parentheses. 95% significance level is t = 2.2 (two-tailed test). Sample size = 21.

Coefficients for model I have the expected sign with the exception of the price difference variable. Household water use decreases with increasing marginal price, and in communities where conservation programs are in effect. This indicates that both pricing strategies and unenforceable appeals (Boulding's (1980) "preachments") can be effective in reducing residential water use. Household water use rises with increasing household income.

The estimated coefficient for p_d is significant and positive, indicating that as p_a increases, holding p_m constant, water consumption increases. This result is clearly unexpected; model III estimates offer a possible interpretation.

Signs for model II parameter estimates are consistent with theory except for the coefficient of D which is large and positive. The ratio β_D/β_M (200, OLS, and 330, 3SLS) giving the relative impact of a unit of income difference to income on water consumption is similar to the results of previous studies shown in Table 5.1. This is likely explained by the correlation between p_d and D; important evidence of this is the high correlation coefficient between p_d and D.

Table 5.4. **Simultaneous equation estimates for municipal demand models, equations (5.6)-(5.8).**

Independent Variables	Dependent Variables p_m	p_d	D
constant	1.47	0.17	-0.025
	(17.7)	(1.5)	(0.9)
D1	-0.81	0.02	0.040
	(11.3)	(0.2)	(1.6)
D2	-0.60	-0.13	-0.016
	(8.9)	(1.5)	(0.7)
D3	-0.44	-0.11	-0.013
	(7.3)	(1.4)	(0.6)
F		0.025	0.0098
		(5.7)	(9.0)
Q	-0.0092	0.0004	0.0016
	(2.4)	(0.1)	(1.1)
R^2	0.91	0.70	0.87

Absolute values of t-statistics are in parentheses. 95% significance level is t=2.1 (two-tailed test). Sample size = 21.

It is difficult to explain the significant positive coefficients on p_d and D in models I and II. If consumers respond to average price rather than marginal price, then p_d would be expected to have a positive coefficient. If consumer decisions were based on marginal price alone then the coefficient should be near zero. The estimated coefficient for D should be insignificant with a small variance. Instead, both OLS and 3SLS estimates are significant and large.

Estimates for model III again have the expected signs with one exception. Economic theory leads immediately to the hypothesis $\beta_F=0$. That is, fixed service charges should have no impact on consumption. This hypothesis is clearly rejected by model III.

An relatively simple interpretation of this result is perverse consumer behavior with respect to water consumption: individuals view a service charge as a right to use water. The higher the charge, the larger the perceived right.[15]

A more subtle and less radical interpretation of Model III coefficient estimates postulates that service charges are levied to finance fixed capital investments in municipal water delivery and treatment systems. If such investments are largely paid off in older areas, high service charges may be highly correlated with new development. Because new development is concentrated largely in the hotter inland areas in southern California, higher water use is expected in those areas. While appropriate climate variables could control for such regional differences, the climate data available for this study may have had insufficient spatial and temporal resolution to explain this effect.

Application of Household Demand Functions to Municipal Demand

The household demand functions estimated above are used to develop the regional benefit function from municipal use of Colorado River water needed used in CRIM. The preferred single household demand function (Model III, OLS) is used together with population and water use estimates to develop aggregate

[15] Fixed, or service charges are often not difficult to discern on a water bill. Alternatively, an approximation to the fixed charge may be available from experience as the lowest bill received during the year.

municipal demand functions for the Metropolitan Water District (MWD) service area in southern California. (MWD is the water wholesaler which operates the Colorado River Aqueduct bringing Colorado River water to the south coast region.)

Municipal water demand functions developed under this methodology are based on single family residential water demand functions. Implicit is the assumption that municipal water users have identical demand functions under all uses. If the benefits of water use are greater in applications other than in single family residential uses, then the methodology gives a lower bound on total benefits from all uses. For example residential use in multifamily structures typically includes a greater proportion of higher valued indoor uses.

Construction of the total municipal demand function is accomplished in two distinct steps. The sample from which household demand function estimates given above are made includes 18 communities in the MWD service area. It is assumed that these communities are representative of all communities served by MWD. A weighted aggregate demand function is first constructed representing communities in the sample; community population determines the weighting. Second, the resulting demand function is scaled such that the quantity demanded at the (population weighted) average marginal price matches 1985 observed water use of 2.82 maf. The water use estimate is for urban water use in the South Coast region of California (California Department of Water Resources, 1988), which closely matches the MWD service area.

Calculation of the municipal demand function uses the OLS estimates for Model III presented in Table 5.3. The choice of Model III is clear from the above discussion; it offers both the best fit and preferable interpretations of consumers' water consumption decisions. Use of OLS estimates are suggested by the small sample. The 3SLS estimators are unbiased, but are only asymptotically efficient. While OLS estimators are biased, their mean square errors are likely smaller given the limited sample size (Rhodes and Westbrook, 1981).

MWD service area demand is aggregated from economic demand for water by its member communities. Household demand in community i is given by

$$q_i(p) = a_i + bp \qquad \text{if } p \leq -a_i/b_i, \qquad = 0 \qquad \text{if } p > -a_i/b_i \tag{5.9}$$

where p is marginal price, b is the estimate of the marginal price coefficient β_m for model III (OLS), and a_i is given for each community by

$$a_i = \beta_0 + \beta_F F_i + \beta_M M_i + \beta_c C_i \tag{5.10}$$

Here β_0, β_F, β_M, and β_c are the coefficient estimates for Model III and F_i, M_i, and C_i are variables representing fixed service charge, income, and the presence of a conservation program in the ith community. A weighted aggregate demand function is constructed by summing over all households. For simplicity, let population estimates n_i for each community be a proxy for the number of households. (The scaling problem with this assumption is corrected when total demand at the average price is set to the observed consumption.) Then aggregate demand $Q_n(p)$, weighted by population, is given by

$$Q_n(p) = \sum_i n_i q_i(p) \tag{5.11}$$

The aggregate demand function (5.11) is shown in Figure 5.1 for prices 0 -\$3,000/af. Aggregate demand is approximated by

$$Q_n(p) \approx \sum_i n_i a_i + nbp \tag{5.12}$$

where $n = \Sigma_i n_i$ is the total population in the sample communities. The approximation is good if the water demanded (from a particular supply source) is nonzero in most communities; if water demanded is nonzero for all communities then equation (5.12) is exact. The solid line in Figure 5.1 shows the approximation given by (5.12). Since this study is concerned only with relatively low water values this simple form is used to represent aggregate water demand. For consideration of demand with very high marginal values expressions in (5.9) and (5.10) should be used.

Dividing the aggregate demand function coefficients by the total population n in sample communities gives household demand for the (population weighted) average single family residence,

$$Q_a(p_m) = 19 - 3.7\, p_m \tag{5.13}$$

where $Q_a(p_m)$ is monthly consumption (1,000 gallons) at marginal price p_m (\$/1,000 gallons).

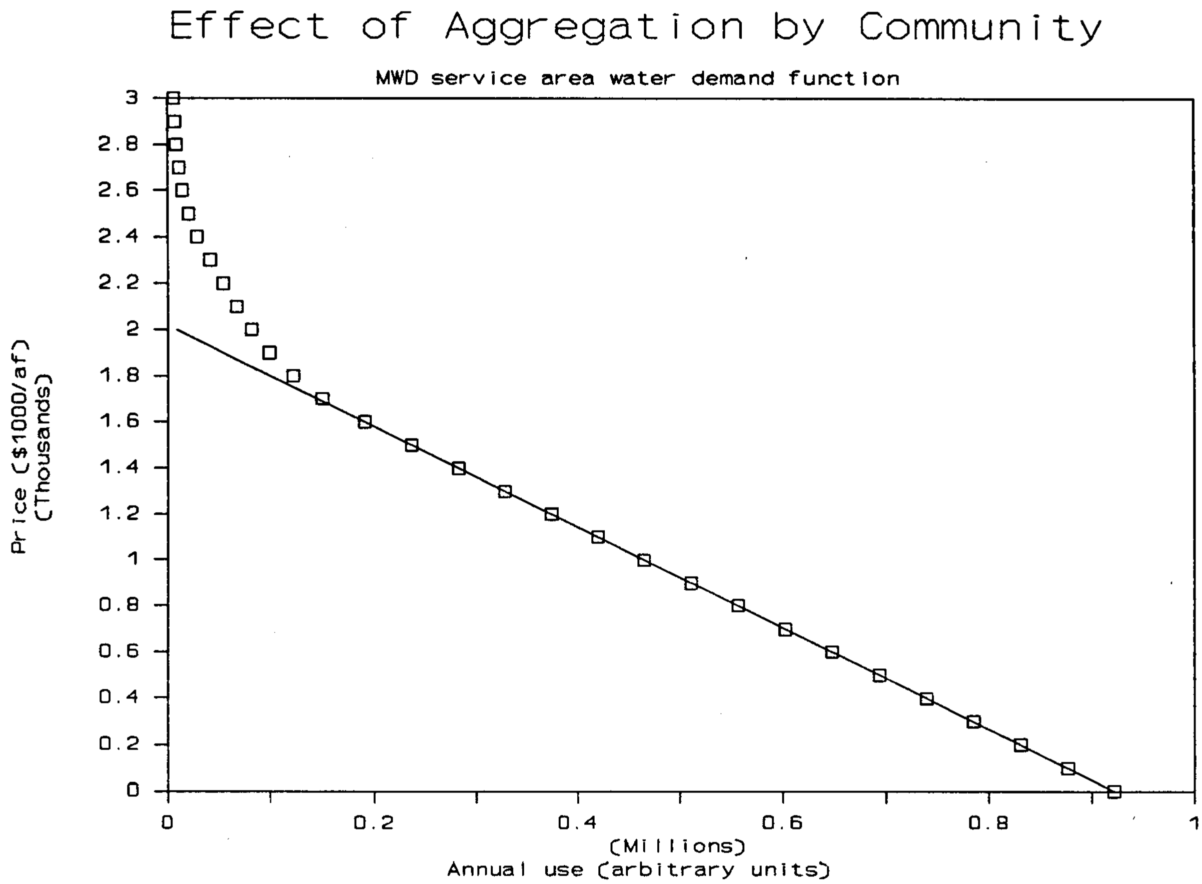

Figure 5.1. Aggregate demand function for communities in sample.

Population and urban use estimates for the South Coast region of California (California Department of Water Resources, 1988) are used as the basis for constructing the total MWD service area demand functions. The 1985 demand function is constructed using the 1985 net urban use estimate of 2.82 million acre-feet (maf). Using the (population weighted) average marginal price of $0.80/1,000 gallons ($260/af) in equation (5.13) with the total observed use, the total MWD service area demand Q(p) (in maf) is

$$Q(p) = 3.23 - 0.0016p \quad (5.14)$$

where p is marginal price ($/af). The aggregate demand function in (5.14) has a price elasticity of -0.15 at the average marginal price and 2.82 maf. Marginal values at 10 percent and 25 percent supply reductions are $430/af and $700/af, respectively. For comparison, Vaux and Howitt (1984) 1980 demand functions for the same municipal area use a price elasticity of -0.40 and an implied price of $240; marginal values at 10 percent and 25 percent supply reductions are $320/af and $430/af, respectively. (Vaux and Howitt's implicit values are adjusted from 1980 to 1985 dollars by the implicit GNP deflator.) Southern California municipal water use rates are taken from Bruvold, Mittelbach, and Werner (1982).

Demand functions for 1990, 2010 and 2030 are determined based on population projections by the California Department of Finance (1986). Proportionate increases in the number of households and constant economic demand per household is assumed. The projected population increases and water demanded at constant prices are shown in Table 5.5.

Table 5.5. **Population, total water use, and linear demand function projections for Colorado River water in the MWD service area.**

Description	1985	1990	2010	2030
Population (million)	14.1	15.4	19.8	22.7
Total water use (maf)	2.82	3.1[a]	4.0[a]	4.5[a]
Inverse demand function coefficients				
constant($/af)	1002	1088	1276	1388
slope($/af/maf)	-669	-613	-489	-416

1989 dollars

[a] The quantity of water demanded in the MWD service area at the 1985 average price for delivered household water of $300/af.

Municipal demand for Colorado River water

Southern California relies on a number of supply sources in addition to Colorado River water. In 1985, only about 30 percent of supplies were derived from imports of Colorado River water. The balance came from imports of Owens Valley and Mono Lake Basin water, California State Project water, and local surface and groundwater development. Determination of municipal demand for Colorado River water should consider the opportunity costs of these alternative supplies. First, all supplies can be used for agricultural purposes; it will be assumed in this section that opportunity costs from foregone agricultural production are roughly constant across all supply sources. Environmental and other third party costs will also be assumed constant. Supply from each alternative source is assumed limited to 1985 levels; this is reasonable in the context of this study, where derived shadow prices for Colorado River water typically would not justify construction of new reservoir and aqueduct capacity.[16]

With these assumptions variations in water quality and energy conveyance requirements are the predominant cost differences between supplies. In particular, the calculation of salinity damages presented in Chapter 6 indicates that Colorado River water causes damages of about $100/af.[17] These damages are temporarily considered here as a cost of utilizing Colorado River water. An energy cost of 40 mills/kwh (1985 dollars) for pumping of alternative supplies is used. Energy requirements are derived from MWD (1988) and Christensen, Harrison, and Kimbell (1982). Figure 5.2 shows the difference between 1985 MWD service area water demand and energy supply costs and salinity damages from alternative supplies. If supply sources are ordered by increasing cost, then the difference between total municipal demand and cost of supply of each source gives the marginal benefit to consumers from consumption of treated, delivered water. In particular, the inclusion of salinity damages causes Colorado River water to be treated as the marginal supply source. Conveyance and treatment costs for Colorado River water only are developed in more detail below.

Conveyance Costs

Colorado River water is delivered to southern California municipal users through the 242 mile Colorado River aqueduct. A total lift of 1,617 feet is required between the intake at Lake Havasu and its terminal reservoir near Riverside. Energy costs of moving water through the aqueduct are believed to be the dominant conveyance costs. In fiscal 1987-88, 2.55×10^9 kilowatt-hours (kwh) were required to transport

[16] This is, however a very strong assumption; it is discussed in the sensitivity analysis presented in Chapter 8.

[17] This figure is based on household damages of $0.26 per mg/l, a salinity difference of 260 mg/l between Colorado River water and other supplies, and 1.42 million affected households.

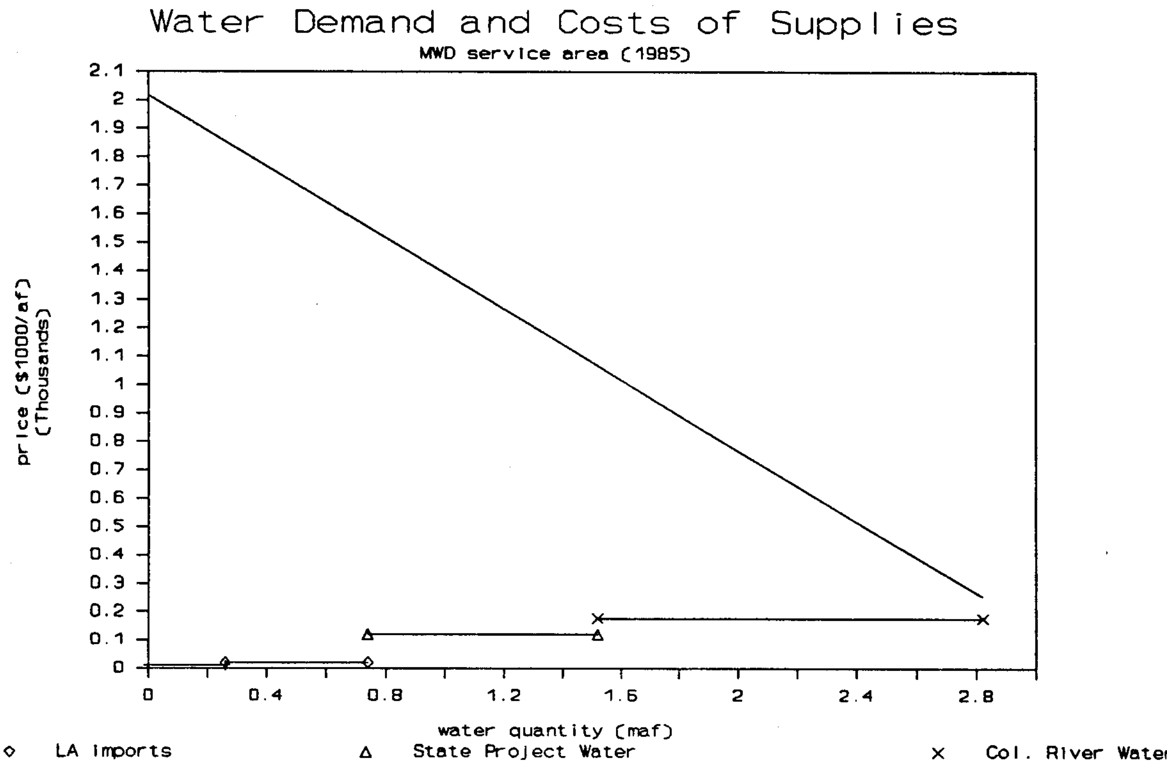

Figure 5.2. **Demand and supply for South Coast region, 1985.**

1.23 maf through the aqueduct (MWD, 1988), giving unit energy requirements of 2,070 kwh/af. Some energy recovery is made from hydroelectric power recovery plants located at metropolitan area storage reservoirs. This offsetting energy production is estimated at 200 kwh/af, giving net energy requirements of 1,900 kwh/af. Using an opportunity cost of 40 mills/kwh (see Chapter 4) gives net energy costs of $76/af. Other operations and maintenance costs are also presumed significant. An estimate of 20 percent of energy costs, or $15/af is used.

Treatment Costs

The Metropolitan Water District serves as a wholesaler of treated and untreated water in southern California. Contracts with local municipalities for all service classes in fiscal 1988-89 reflected a premium of $33/af for treated versus untreated supplies (MWD, 1988.) This can be taken as a measure of treatment costs for Colorado River water.

Present and Future Demand for Colorado River Water

Incorporating all delivery related costs and using the MWD service area demand function shown in Figure 5.1 gives the demand for raw Colorado River water at Lake Havasu. After adjustment to 1989 price levels the 1985 municipal demand for raw Colorado River water varies from $1000/af for initial deliveries to $130/af at the aqueduct capacity of 1.3 maf/year. Population growth increases the marginal value to $290/af by 1990.

Table 5.5 gives resulting inverse demand functions (not including salinity damages) for use in CRIM for years 1990, 2010, and 2030, at 1989 price levels.

CHAPTER 6
MUNICIPAL SALINITY DAMAGES FROM COLORADO RIVER WATER

Salinity in municipal water is known to lessen the useful lifetime of plumbing and appliances, and require increased use of soaps and detergents. At high salinity levels some consumers may purchase bottled water as a substitute for municipal water for drinking and cooking. Estimation of economic damages has been undertaken in several studies, but damage estimates remain highly uncertain (Gardner and Young, 1985, and Lohman, et al. 1988).

Salinity levels are measured by total dissolved solids (TDS) per unit volume. Physical damages from salinity are a function not only of the total concentration, but of particular mineral constituents which may vary significantly across different water sources. Colorado River water includes calcium, magnesium, sodium, bicarbonates, chlorides, and sulfates (Miller, Weatherford, and Thorson, 1986). The complex chemistry underlying scaling and corrosion of water fixtures is affected by both salt concentrations and composition.

There is some suggestion and evidence (Lohman et al., d'Arge and Eubanks, 1978, McGuckin, 1977) that salinity damages are non-linear in salinity concentration. Because this effect is not well understood, constant marginal damages from salinity concentration are assumed in this study. Further, the effect of varying salt composition, which is almost certainly significant (d'Arge and Eubanks), is not considered because of limited data. Previous studies have generally relied on surveys of households or appliance dealers and plumbers across communities to develop salinity damage estimates.

Previous Work

The salinity damage estimates used in this study are derived from a synthesis of primary data from several sources made by Lohman et al. The studies identified as using original, independent data include Black and Veatch (1967), Tihansky (1974), d'Arge and Eubanks, California Department of Water Resources (1978), Patterson and Banker (1978), and Coe (1982). Estimates of household municipal damages are given by Black and Veatch, McGuckin, Kleinman and Brown (1980), and Gardner and Young. These estimates are summarized in Table 6.1. Household damage estimates developed here include only the damage categories used in these previous studies. Additional damages calculated by Lohman et al. (particularly to automobiles, and commercial and municipal property) are viewed as speculative given the limited data on which they are based. The implication of these resulting high estimates on the value of Colorado River water is discussed below.

Calculation of Annual Damages

Calculation of annualized damages implicitly assumes an age distribution of existing appliances and fixtures. Consider a good of physical age[18] t with lifetime t′. Let the cost of replacing the good be $1. The present value cost PV_t of replacing the good (an appliance, for example) over a time period T (the lifetime of a house containing the appliance) is given by

$$PV_t = e^{-r(t'-t)} + e^{-r(2t'-t)} + \ldots + e^{-r(nt'-t)} - f(t)e^{-rT} \qquad (6.1)$$

where $T-t \le nt' < T$, $f(t) < \$1$ is the salvage value of the good at time T, and r is the interest rate. Now let N(t) be the probability density function of goods of age t. Then the average unit present value cost PV of replacing goods of all ages t is

[18] If a change in environmental conditions occurs then chronological age of a good may exceed its expected lifetime under the new environmental conditions. Age is then interpreted as the time required under the new conditions to give the present level of aging.

Table 6.1. **Economic damage estimates from salinity from previous research.**

Source	Household Damages ($/mg/l)	Total Damages ($1,000/mg/l)
Black and Veatch (1967)	0.382	688
McGuckin (1977)	0.111	200
Kleinman and Brown (1980)[a]	0.261 (0.14-0.31)	470 (252-558)
Gardner and Young (1985)	0.277	499
Lohman, et al. (1988)[b]	0.263	459

Total damages for all sources are estimated on the basis of 1.8 million affected households. All figures adjusted to 1989 dollars using the consumer price home and maintenance index.
[a] Figures in parentheses are ranges based on the estimated standard error.
[b] Household damages based on calculations summarized in Table 6.2 from data by Lohman, et al. (1988). Alternatively, household damages from 500 mg/l to 600 mg/l calculated directly using a computer program developed by Lohman et al. gives $0.484 per mg/l per household. This higher figure is based on inclusion of automobile radiator damages and other factors. For comparison with the other studies, an "escalation factor" of 1.53 (to value damages in public buildings and commercial establishments) is not included in figures given here.

$$PV = \int_0^{t'} N(t) \left[\sum_{n=1}^{T/t'} e^{-r(nt'-t)} - f(t)e^{-rT} \right] dt \tag{6.2}$$

which can be rewritten as

$$PV = \sum_{n=1}^{T/t'} e^{(-rt')n} \int_0^{t'} N(t) \left(e^{rt} - f(t)e^{-rT}\right) dt \tag{6.3}$$

This expression can be used as the basis for calculating the present value of all costs required in replacing a good over a period T.

Now consider two particular cases. The first case considers a uniform age distribution given by $N(t)=1/t'$. The second case assumes that all goods are new; that is $N(t)=\delta(0)$. In both cases let $T \to \infty$. This assumption is equivalent to assuming that the good needs replacement exactly when its use (in a household or automobile) is no longer needed,[19] and an infinite planning horizon is used. The effect is that $f(t)e^{-rT}=0$ in equation (6.3). This is virtually identical to the 60 year household life with full salvage value used by Kleinman and Brown and McGuckin.

The first case of a uniform age distribution gives the unit present value of costs

$$PV = \sum_{n=1}^{T/t'} e^{(-rt)n} \int_0^{t'} e^{rt} /t \; dt \tag{6.4}$$

The summation is performed using the result

[19] Equivalently, if salvage is possible at full value using straight-line depreciation then this restriction is unnecessary.

$$\sum_{t=1}^{\infty} e^{-at} = 1/(e^{a} - 1) \tag{6.5}$$

Evaluating the integral and using (6.4) gives immediately PV=1/rt′. Annualizing over an infinite time horizon using AV=rPV gives AV=1/t′. This simple result, independent of the discount rate, is obtained because a steady state process was assumed: each year a constant number of goods needs replacement. The number needing replacement is a function of environmental conditions expressed as the expected lifetime t′.

In the second case considered for comparison, all goods are initially new. Then (6.3) becomes

$$PV = 1/(e^{rt'} - 1) \times 1 \tag{6.6}$$

since $\int_0^{t'} \delta(0)\, e^{rt}\, dt = e^{r \cdot 0} = 1$. The annualized unit costs are then given by $r/(e^{rt'}-1)$.

Household Damage Estimates

Annual salinity damages are calculated under the two alternative assumptions of initial age distributions discussed above. Table 6.2 shows the data from Lohman et al. used to estimate damages. The difference in replacement costs between 600 mg/l and 500 mg/l salinity concentrations is used as the basis for the household damage estimates. The household damage estimates for durable goods is $0.136 per mg/l using a uniform age distribution versus $0.105 per mg/l (1986 dollars) using all new durable goods, a difference of 30 percent. Though assumptions on the initial age distribution have a significant impact on annual damage estimates, the difference is nevertheless believed smaller than the uncertainty in the underlying data. An additional category of damages which occur on a continuing basis do not require assumptions on age distributions. These additional damages, again from Lohman et al., are also given in Table 6.2 to give total household damage estimates of $0.218 to $0.249 per mg/l (1986 dollars). Damages to automobile radiators reported by Lohman et al. are judged to be speculative and are not included in the household damage estimates presented here.

Total Damages from Colorado River Water

Total municipal area damages are found from the damages per household calculated above by summing over all households using Colorado River water. A uniform age distribution of household fixtures and appliances is assumed, giving household damages of $0.263 per mg/l in 1989 dollars. The number of households damaged (blending of water supplies is neglected because damages are linear by assumption) is estimated assuming typically annual delivery of 1.23 maf. Using 1.42 households/af (the 1985 average consumption by single family residences reported in Chapter 5) gives 1.75 million affected households and total household damages of $459,000 per mg/l. Industrial and utility damages are not explicitly included because they are believed small, with great uncertainty about their magnitude. Damages to commercial and municipal facilities may be significant since they contain plumbing and some appliances common to those found in households, but are excluded from the total damage estimate used in this research.

Future damages are found by increasing damages proportionally to expected population increases given in Chapter 5 for the MWD service area. Damage estimates and population figures are presented in Table 6.3 for 1990, 2010, and 2030.

Discussion of Salinity Damage Estimates

Actual damages from use of saline water in southern California urban areas is dependent on many factors beyond the scope of this study. Colorado River water is mixed with other supplies before distribution; water delivered to residences thus has significantly lower salinity levels than that imported from the Colorado River. The assumption of linearity in salinity damages makes the actual level of mixing unimportant in evaluating marginal damages from salinity imports. The complexity of salinity damage chemistry is not considered here.

Table 6.2. Annualized salinity damages for durable goods and recurring expenses.

Item	Cost ($)	Number	Years to Replacement 500 mg/l	600 mg/l	Annual Cost Uniform[a] ($/mg/l)	New[b] ($/mg/l)
Water pipes	1,200	1	24.3	22.2	0.047	0.036
Waste water pipes	3,000	1	42.6	40.7	0.033	0.013
Water heaters	184	1	9.4	8.7	0.016	0.016
Faucets	75	3.9	10.1	9.8	0.009	0.009
Garbage grinders	125	0.8	7.4	7.1	0.006	0.006
Toilet flushing	3.24	1.5	8.2	7.6	0.000	0.000
Clothes washer	446	0.6	9.6	9.0	0.019	0.018
Dish washers	417	0.25	9.6	9.0	0.007	0.007
Sub-total, damages to durable goods					0.136	0.105
Water softeners[c]	205	1	17.5%	21.0%	0.072	0.072
Bottled water[d]					0.030	0.030
Soaps & Detergents[d]					0.001	0.001
Clothes Replacement[d]					0.010	0.010
Sub-total, recurring expenses					0.113	0.113
Total household damages					0.249	0.218

Based on data in Lohman et al. (1988).
1986 dollars
8.875% discount rate
[a] Uniform initial age distribution for household durables.
[b] All household durables assumed new when salinity concentration changes.
[c] Calculated based on half of units rented at $264/year and half purchased at $626. Annual cost of purchased units based on 10 year lifetime with $5.74/month operation and maintenance costs. Percentages reflect estimated number of households using water softeners at differing salinity levels.
[d] Annual values taken directly from computer program developed by Lohman et al.

Table 6.3. Projected affected households and total salinity damage estimates from Colorado River water.

	1990	Year 2010	2030
Households (million)[a]	1.75	2.25	2.55
Damages ($/mg/l)	500,000	640,000	730,000
Damages ($/ton)	280	360	410

1989 dollars
MWD service area, based on annual deliveries of 1,300 kaf.
[a] After 1990 the effective number of households is assumed to increase proportionally to population. This is equivalent to assuming that Colorado River water continues to satisfy a constant proportion of area water deliveries.

Future Salinity Damages

The number of households served by imported Colorado River water in the future is uncertain. If water supplies to southern California do not increase significantly as population increases, then the number of households served by a unit volume of Colorado River water must rise with population. Further, if present trends continue and average household size declines in the future, then the number of households per unit of water must increase independent of population increases.

Damages are largely dependent on water-using plumbing and appliances. With rising incomes, households can be expected to employ increasing numbers of such items, thus increasing damages per household. Conversely, increasing use of non-metallic plumbing, and fixtures which show little loss in lifetime from salinity (Kleinman and Brown) may significantly decrease damages.

Damage Estimates in Perspective

Many assumptions underlie the damage estimates presented here. The objective of this chapter is to present the best possible estimate of total damages from use of Colorado River water in southern California municipal areas. Any estimate of household damages can be expressed as damages per unit volume of delivered water. For example, using the household damage estimate of $0.26 per mg/l, 1.42 households/af, and a salinity concentration of Colorado River water of 675 mg/l versus an average of 415 mg/l for alternative California supplies, gives damages of $0.26 /(mg/l)·household x (675-415) mg/l x 1.42 households/af = $130/af for use of Colorado River water. For comparison, 1985 marginal benefits from use of Colorado River water estimated in Chapter 5 range from $130/af to $1,000/af. Because the estimates here show marginal benefits from use of Colorado River water at the Aqueduct capacity to equal damages, the salinity damages presented here may be overestimates.

The full damage estimates presented in Lohman et al. appear unreasonably high. Including automobile radiator damages and an "escalation" factor for non-household uses, salinity damages estimated in that report are $0.74 per mg/l per household. Under the above assumptions, this gives damages of $270/af of delivered Colorado River water. If salinity were recognized as to be as damaging as these figures indicate, significant pressure to limit imports of Colorado River water would be expected, particularly in years of high Colorado River salinity and relatively abundant local supplies. As Miller, Weatherford, and Thorson (1986) note, there appears to be remarkably little public concern in southern California regarding salinity in water supplies.

CHAPTER 7
THE COLORADO RIVER INSTITUTIONAL MODEL

The analytic core of this research is the economic optimization model CRIM (Colorado River Institutional Model) linking river flows, salinity concentrations, and demand sectors across river locations. Consumptive use benefits, hydropower benefits, and costs and benefits of salinity production are incorporated as integral model components. CRIM is formulated as a two commodity flow optimization problem with the objective of maximization of net economic surplus (defined over selected economic sectors), subject to physical and institutional constraints. Economic surplus is a function of levels of the two commodities, water quantity and salinity at the economic demand sectors. Fourteen nodes represent the active economic sectors considered for this study. An additional six nodes are used for significant sources or depletions of river water and salt loads, or for important geographical or institutional features. For purposes of this study, uses of basin water in these latter sectors are considered exogenous; shortfalls are imposed only by the present institutional allocation priorities. These sectors and uses are referred to as "excluded," since they are not included in modeled water transfers.

The mathematical programming model is constructed using the GAMS higher level language (Brooke, Kendrick, and Meeraus, 1988) and is solved using the MINOS optimization program developed by Murtagh and Sanders (1980). The model specification is first described below. Considerations specific to particular institutional scenarios are then discussed. Six model definitions are then introduced, corresponding to differing water flow and demand levels.

General Model Specification

The annual long run producer and consumer surplus functions developed in previous chapters are used directly in the objective function definitions of eight institutional scenarios. The remaining scenario closely approximates present allocation and requires allocation by institutional priorities without regard to economic value. Ten-year average flows consistent with a given reliability level are used to simulate the water supply. Flow levels are defined here by the probability of ten-year average flow levels above or below a specified level. For lower decile flow levels presented in the model definitions below, 90 percent of ten-year average flows are above and 10 percent below the lower decile flow. This follows terminology used in a USBR (1986c) study of Colorado River management. Use of ten-year averages is justified by the large storage capacity in the basin and is based on the 1922 Compact requirement specifying delivery of 75 maf to the lower basin every 10 years.

The numerous diversion points not explicitly treated in this analysis are modeled by assumed request levels given in USBR (1986b). These are satisfied according to institutional rather than economic priorities. Institutional allocation rules are incorporated in objective function definitions and as explicit constraints. Physical and monetary units used internally by CRIM are given in the List of Abbreviations, Units, and Definitions.

The conceptual basis and structure of CRIM is outlined below. The model utilizes twenty nodes, each with possible economic demand, supply, and request levels. A representation of the model is shown in Figure 7.1, where the economic sectors at each node are explicitly shown. The basin is modeled as a single mainstem with all demand and supply sectors occurring as simple tributaries or diversions. Above the Colorado-Green River confluence the Green River is chosen as the mainstem.

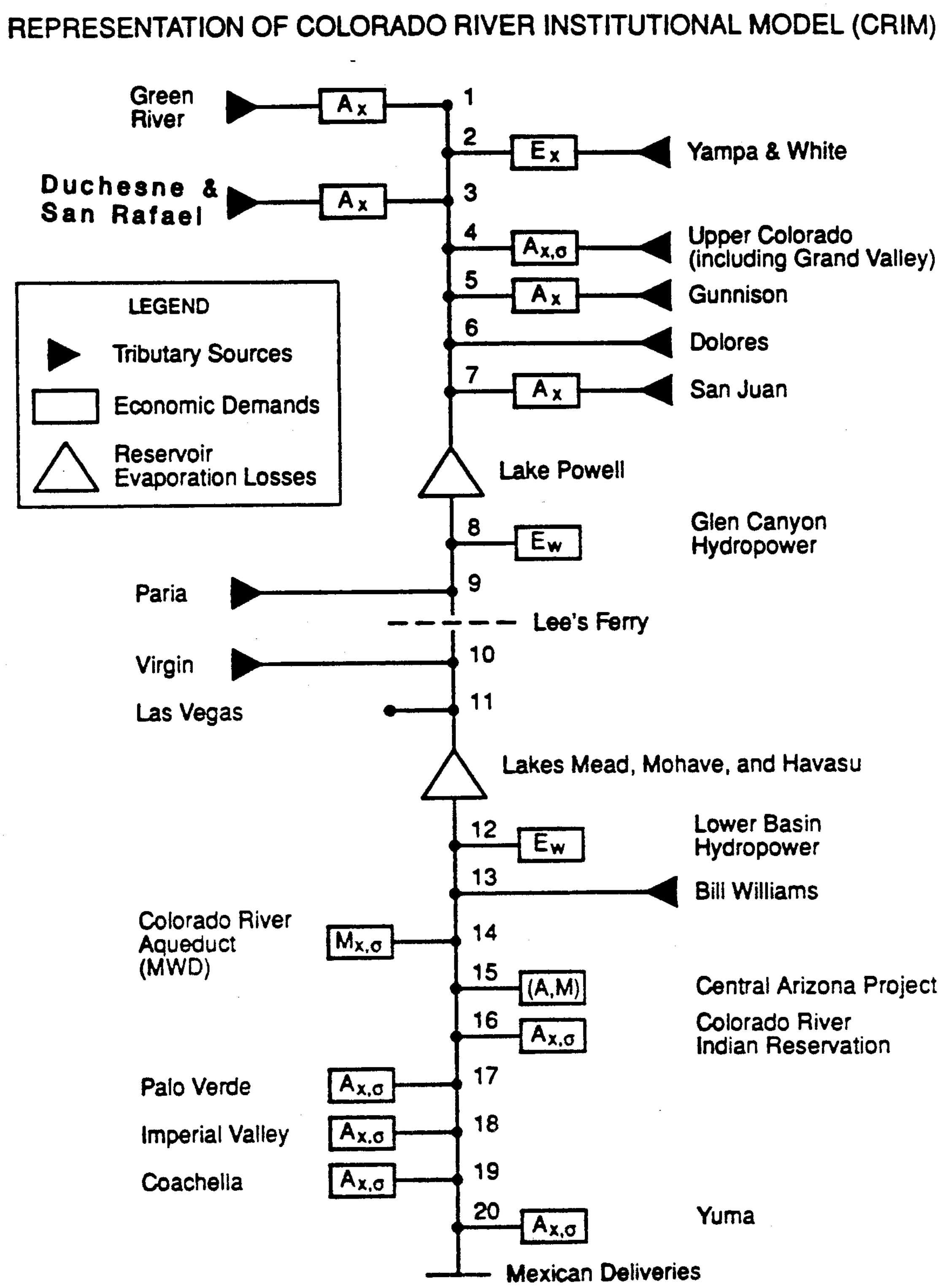

Figure 7.1. **Schematic representation of CRIM formulation.**

Physical Constraints

The first constraint equation (a mass balance constraint) balances total flows and consumptive uses:

$$Q_i = Q_{i-1} - V_{i-1} - x_i + Q_i^a + Q_i^f \tag{7.1}$$

where

Q_i total flow leaving node i
Q_i^f tributary flow into node i
Q_i^a net flow adjustment for inflows and uses between i and i-1 (including reservoir releases from storage)
x_i total consumptive use at i
V_{i-1} evaporation losses between i and i-1.

Equation (7.1) is the fundamental relation governing the physical transfer of water between economic demand sectors. A similar relation governing salinity accounting is given below. All mechanisms for water loss and gain in the river system are included in the definitions supporting equation (7.1). Figure 7.2 shows a schematic representation of the mass balance equation.

One supporting definition and two physical constraints are included to complete the basic water quantity accounting. These are

consumptive use: $$x_i = \bar{x}_i + \sum_i \eta_{ij} w_{ij} \tag{7.2}$$

mainstem withdrawals: $$x_i \leq Q_i \tag{7.3}$$
tributary withdrawals: $$x_i \leq Q_i^a \tag{7.4}$$

where

$\bar{x}_i$ requests for (excluded) consumptive use at i
w_{ij} withdrawal for economic purpose j at node i.
η_{ij} irrigation efficiency of (economic) withdrawal j at node i.

Efficiency of water exports from the basin are defined to be 1, since there are no basin return flows. Diversions for hydropower generation are set equal to the river flow leaving the node at which the hydropower plant is located. Evaporation from basin reservoirs is a significant factor in the basin water budget. It is reasonably accurate to express evaporation as a linear function of average flows; the derivation of evaporation rates is given in the Appendix.

A single mass balance constraint equation is used to handle salinity accounting:

$$\sigma_i = \sigma_{i-1} + \sigma_i^n - \sigma_i^x \tag{7.5}$$

where

σ_i total salinity leaving node i
σ_i^n net salinity addition from all sources between i-1 and i
σ_i^x salinity exports from out of basin diversions.

Precise salinity accounting using linear constraints is possible using the mass of total dissolved salts rather than concentrations. At exporting nodes a nonlinear constraint is required, however. Since salinity exports are given by

$$\sigma_i^x = \sigma_{i-1} (w_i/Q_i) \tag{7.6}$$

some nonlinear constraints must be used. Economic damages based on concentrations appear only in the (nonlinear) objective function. Net salinity additions are given by

$$\sigma_i^n = \bar{\sigma}_i + \sum_i \sigma_{ij}^a \tag{7.7}$$

where

$\bar{\sigma}_i$ net salinity addition from fixed human and natural sources
σ_{ij}^a salinity production from the jth economic purpose at node i.

ILLUSTRATION OF MASS BALANCE CONSTRAINT

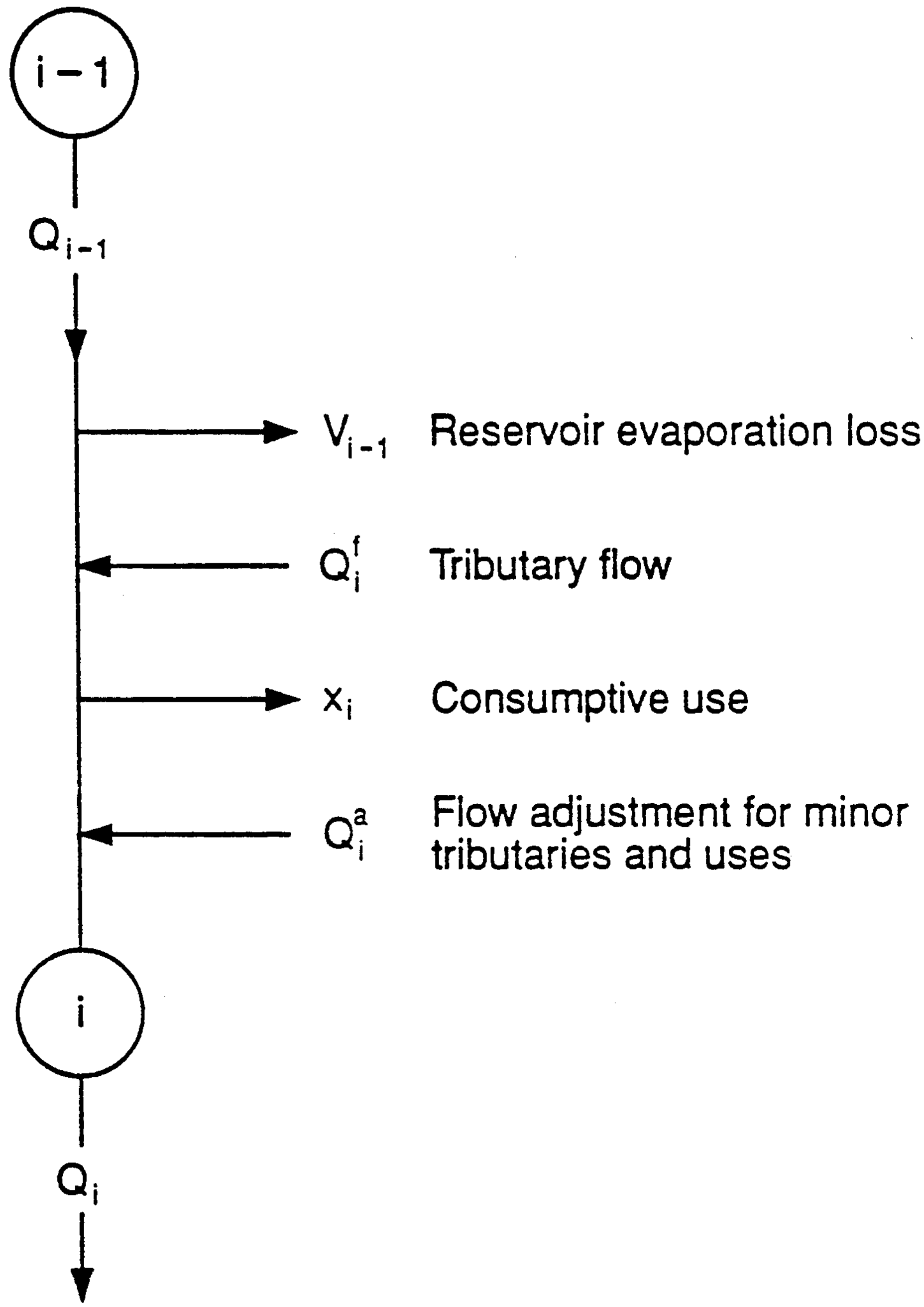

Figure 7.2. Representation of quantities used in mass balance constraint.

General Objective Function

The objective in a typical institutional scenario is to maximize net economic surplus from selected economic demand points

$$\max \sum_i \pi_i(w_i, \sigma_i/Q_i) \qquad (7.8)$$

where

$\pi_i(w_i, \sigma_i/Q_i)$	net benefits at demand point i from
w_i	total withdrawals at i, and
σ_i/Q_i	salinity concentration at i, where
Q_i	total flow at i, and
σ_i	total dissolved salts at i.

For simplicity, only single economic demands at each node are assumed in equation (7.8).

The profit and consumer surplus functions used in the objective function are expressed as net benefits (and salinity costs) from withdrawals at the river. Conveyance costs are thus only implicit in the model; they are not the focus of this study. All conveyance costs are included in the profit and consumer surplus function definitions. Use of withdrawals simplifies incorporation of instream hydropower benefits. Specific constraints imposed on specific scenarios to simulate the institutional environment are discussed below.

Modeling of Institutional Scenarios

The focus of this study is the investigation of impacts of alternative institutions on Colorado River water users from a national and regional perspective. Accordingly, deliveries to Mexico of 1.515 maf are required in all institutional scenarios under all model definitions. This requires $Q_{20} \geq 1.515$ maf, the level specified in the 1944 U.S.- Mexico treaty.

The institutional scenarios considered here are grouped into three categories. The first category (Group 1) includes scenarios which do not require changes to existing rules governing interstate allocation of basin water. The second category (Group 2) of scenarios allows both intrastate and interstate transfers for purposes of increasing economic benefits from consumptive uses of basin water. The third category (Group 3) incorporates the broadest range of economic values, allowing intrastate and interstate transfers for satisfying economic values in consumptive uses, hydropower generation, and salinity loss reduction. Table 7.1 summarizes the active economic values in each institutional scenario. Grouping and numbering of scenarios in the table follows that given below in the description of alternative institutions.

Group 1: Allocation in Compliance with Compact Priorities

The first institutional scenario (Scenario 1) does not include economic values in the allocation decision. Rather, existing priorities, both intrastate and interstate are followed in allocating limited supplies between competing uses. Delivery of 8.25 maf/year at Lee's Ferry is required as the fundamental upper basin obligation.

The delivery obligation is imposed by the simple constraint $Q_9 \geq 8.25$ maf. All upper basin uses are reduced by equal proportions[20] to meet any shortfalls at Lee's Ferry. Lower basin allocation is modeled by three priority levels. Highest priority is delivery of 0.55 maf to the MWD service area, plus all other lower basin users excepting the Central Arizona Project. The next priority is delivery to the Central Arizona Project. The lowest priority is "surplus" water presently used by MWD, up to the Aqueduct capacity of 1.30 maf (including the high priority 0.55 maf). The objective function for allocation by institutional priorities is

$$\pi(s_{ub}, s_{14}, s_{15}) = s_{14} + 2s_{15} + 3s_{ub} \qquad (44)$$

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[20] Minor uses included in the net flow adjustment Q_i^a used in equation (35) are satisfied in full. All major uses in both economic and excluded sectors share in the reduction.

Table 7.1. Summary of sectors used in different institutional scenarios.

		Scenario number								
		Group 1		Group 2		Group 3				
Demand Sector		1	2	3	4	5	6	7	8	9
Grand Valley agriculture		P	X	X	X	X	X	X	X	X
Other Upper Basin Agriculture		P	X[a]		X			X	X	X
Upper Basin Energy		P	X	X	X	X	X	X	X	X
Other Upper Basin uses		P								
Upper Basin Hydropower						X		X		X
Lower Basin Hydropower						X		X		X
Imperial Valley ag.:	water use		X	X	X	X	X	X	X	X
	salinity damage						X		X	X
Other California Agriculture					X			X	X	X
	salinity damage								X	X
MWD service area:	water use	P	X	X	X	X	X	X	X	X
	salinity damage						X		X	X
Central Arizona Project		P								

Key to sector roles in objective functions:
P-priority of water right included
X-net benefit function included
[a]Omitted for historic lower decile flow series.

where s_{ub}, s_{14} , and s_{15} are shortages experienced by upper basin users, MWD, and the Central Arizona Project, respectively.

An alternative to allocation by existing priorities is water allocation maximizing consumptive use benefits given each states' water allocation under the Compact priorities. This case (Scenario 2) may be the most realistic representation of the evolving institutional arrangements governing allocation of Colorado River water. In the context of this model, intrastate trade allows transfers between the Imperial Valley and southern California municipal demand. Transfers between the Colorado thermal energy production sector and the Grand Valley irrigation sector are also allowed. In those model definitions (presented below) inducing large upper basin shortfalls, all major upper basin agricultural sectors are included in the scenario. In this case, transfers are not strictly limited by state boundaries, but could include transfers between upper basin states. While such transfers are unlikely, the assumption greatly simplifies modeling this scenario. Transfers which are estimated under this scenario could easily be approximated by intrastate transfers only. Benefits of hydropower production and damages from salinity are not considered in determining water allocation under this scenario.

This intrastate institutional scenario is modeled using a single objective function including only consumptive use values in the economic sectors. The Lee's Ferry delivery constraint of 8.25 maf/year is used. Shortfalls to excluded sectors in the upper basin and the Central Arizona Project (the sole excluded lower basin sector which suffers shortfalls) determined under the existing priorities are retained.

Group 2: Interstate Transfers for Consumptive Uses

This group is significant because the fundamental constraint on deliveries from the upper basin required under the Compact is removed. Two scenarios are used which allow interstate transfers between economic demand sectors for increasing consumptive use benefits. The first (Scenario 3) includes only demand sectors specifically modeled or addressed in previous chapters. The second (Scenario 4) expands the economic demand sectors to the major upper and lower basin and California agricultural users. In this scenario it is assumed that all upper basin agricultural water demand, normalized to present request levels, follows the demand function estimated for the Grand Valley. All California agricultural requests are assumed to follow the form estimated for the Imperial Valley.

Scenario (3) optimizes economic benefits from use of basin water in Yampa and White River thermal energy production, Grand Valley agriculture, MWD municipal deliveries, and Imperial Valley agriculture. Scenario 4 includes economic demands by an additional eight agricultural sectors in the optimization problem.

Group 3: Scenarios Incorporating Nonconsumptive Use Values

This group of scenarios includes economic values from nonconsumptive use of basin water resources in addition to the traditional consumptive use values in the allocation decision. Five scenarios are included in this category. Two scenarios include only explicitly modeled sectors; the remaining three include the additional upper and lower basin agricultural demand sectors.

The first two scenarios in this category include consumptive use benefits and either hydropower benefits (Scenario 5) or salinity losses (Scenario 6) in the optimization problem. The remaining institutional scenarios include the expanded agricultural demand sectors, and utilize consumptive use benefits and hydropower benefits (Scenario 7), salinity losses (Scenario 8), or both hydropower benefits and salinity losses (Scenario 9) in the optimization problem.

The scenarios differ only in the economic values and sectors allowed to bid; the objective function shown in equation (7.8) is defined by summing over the i active economic demand sectors in each scenario. In the full trade scenario (Scenario 9) the summation is over all consumptive and nonconsumptive uses, including benefits and costs of consumptive water use, hydropower production, and salinity production, and damages from salinity. The other scenarios in this group restrict objective function benefits and costs to consumptive use sectors plus hydropower production only, and salinity damages only, respectively.

Discounting of Salinity Damages

Actions to reduce upper basin salinity production do not immediately result in lower salinity concentrations to downstream users of Colorado River water. Similarly, there is a time lag for changes in upper basin dilution to be reflected in changed lower basin salinity levels. Following Gardner and Young (1985), and Lee (1989), the values of changes in lower basin salinity levels are discounted to reflect the estimated salinity retention time. A simple four-year lag suggested by Lee as representing modeled results from studies using the Bureau's CRSM (see USBR, 1986a) is used together with an 8 percent discount rate. Benefits of salinity reduction are thus lowered by 26 percent. This is similar to the discount factor used by Gardner and Young, calculated from a distributed six-year lag function.

Consumptive Use Requests

Other than sectors explicitly discussed in previous chapters, requests for consumptive use of basin water are taken from input data for the Colorado River System Model (USBR, 1986b). Explicit modeling of other requests was beyond the scope of this study. Table 7.2 gives the request levels (corresponding in many cases to total water rights held in each river reach) used in the present study.

Where explicit modeling was performed, request levels are adjusted to reflect this work. In particular, Grand Valley agricultural consumptive use is assumed limited to 163 kaf, the maximum use determined by the Grand Valley linear programming model. (An additional 10 kaf is included in excluded requests for high valued fruit crops.) MWD diversions for delivery to the California south coast metropolitan area are assumed limited only by the Colorado River Aqueduct capacity. USBR (1987) reports diversions of 1,303 kaf for water year 1987; this is used as the aqueduct capacity. Imperial Valley use was found in the linear programming model to be 2,710 kaf (after including delivery losses of 270 kaf), significantly less than the maximum 3,010 kaf request reported in USBR (1986b). This finding is supported by Bureau of Reclamation figures (USBR, 1982-87) showing the maximum diversion to the All-American canal for use in Imperial Valley agriculture was 2,640 kaf in the 1982-87 period.

Central Arizona Project (CAP) diversions are a critical component of the lower basin water budget; for water year 1990 diversions of 850 kaf are assumed.

Flow Assumptions

The base model run uses a lower decile ten-year flow, expressed as the average annual flow over this period. The ten-year period is defined as that with 10 percent of all ten year flows lower and 90 percent higher than the lower decile period, over 1906-1983, the years for which historical flow data is available. Table 7.3 shows the average annual flows for the lower decile period 1960-69 and for other selected flow levels. The total basin supply (excluding flows from the Gila River and its tributaries) for this period was 14.3 maf; the reconstructed virgin flow at Lee's Ferry averaged 13.0 maf.

A synthetic low flow model is constructed to represent a more serious drought than given by the base flow levels. This model assumes that the historical flow record presented here (1906 to 1983) is not representative of future conditions. Two factors can be used to support such an assumption. First, application of streamflow reconstructions from tree rings suggests that the long term virgin runoff at Lee's Ferry is only 13 maf/year (Stockton, 1975). In contrast, the 1906 to 1983 period has average annual flows of 15 maf. Second, predictions of rising global temperatures from anthropomorphic emissions of carbon dioxide and other greenhouse gases suggest the possibility of decreased runoff in the basin resulting from climate change.

The low flow model is constructed in analogy with the lower decile flows developed from the historical record and used in the base model. Stockton gives 17 maf^2 as the annual variance of reconstructed upper basin flows. Assuming a normal distribution[21] for annual flows, ten year average flows are normally distributed with mean 13 maf and variance $17/10 = 1.7\ maf^2$. Ten percent of ten year average flows lie below 1.28 times the square root of the variance, or below $13.0\text{-}(1.28)(1.7)^{1/2} = 11.3$ maf. It is believed that this represents a realistic flow level which has a high probability of occurrence in the next 40 years. There remains a significant chance that even lower flows could persist over significant periods. It is worth noting that under the long term flow assumptions presented here, the base model flow level represents the mean flow level. If Stockton's reconstructed flows are good estimates of future flow levels, then lower decile flows from the historical record represent normal, rather than drought conditions.

Reservoir Releases

In the event of serious drought, basin reservoirs would be utilized to provide additional water supplies. Simulation results presented in USBR (1986c) are used to develop estimates of average annual net withdrawals from storage under the flow levels presented above. With present (year 1990) demand and request levels, 220 kaf/year is assumed released from Lake Powell under historical lower decile flows. With the higher future (2010 and 2030) demand and request levels, 490 kaf/year is assumed released from basin storage. Under the synthetic lower decile flows simulating a more serious drought, total releases from storage of 800 kaf annually are assumed.

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[21] This is not strictly valid; the long term distribution is probably skewed. From the historical record, average annual upper basin flows are 15.0 maf, but the median flow (for ten-year averages) is 14.5 maf. A calculation using a normal distribution with the historical flow overestimates the decile flow level by 0.3 maf.

Table 7.2. Estimated consumptive use request levels for years 1990, 2010 and 2030.

Reach Location	CRSS#[a]	Type of Use	1990	Year 2010	2030
Upper Colorado	100		938	1054	1141
Blue Mesa	200		63	73	83
Crystal Reservoir	220	ag	96	396	396
		other	21	36	36
Grand Valley	300	ag	163	180	199
		other	22	27	30
Dolores River	310		48	48	48
Fontenelle	401	energy	92	156	214
		ag	187	197	198
Flaming Gorge	411		162	175	183
Yampa	500	energy	13	70	70
		ag	119	165	167
White River	510	energy	0	20	68
		other	46	88	89
Lower Green	600		124	167	210
Duchesne	610		553	664	664
Lake Powell	700		51	57	50
San Rafael	710		94	94	97
Navajo Reservoir	801		487	761	762
Lower San Juan	802		260	305	305
Grand Canyon	900		0	0	10
Virgin River	905		49	68	68
Lake Mead	910		152	236	286
Lake Mohave	920		164	181	181
Lake Havasu	930	CAP	850	1500	1500
		MWD	1300	1300	1300
		other	120	123	123
Above Imperial Dam	940	Col. Ind.	398	431	431
		Palo Verde	423	423	423
		other	333	334	335
Imperial Dam	945	IID	2640	2917	3223
		Coachella	344	344	344
		Yuma	662	662	662
		other	96	106	113
Below Imperial Dam	950	Mexico	1515	1515	1515
		other	29	25	14
Upper Basin Total			3839	4733	5010
Lower Basin Total			7560	8650	9013
Deliveries to Mexico			1515	1515	1515
Total			12,900	14,900	15,500

[a] Numbered reaches used by Colorado River Simulation System (USBR, 1986b).

Table 7.3. Selected ten-year annual average virgin flow estimates for the Colorado River basin.

Description of Gauging Station	CRSS #[b]	Starting year of ten year period for historic flows							Synthetic inflow[a]
		1931	1960	1950	1937	1923	1917	1914	
		lowest	lower decile	lower quartile	median	upper quartile	upper decile	highest	lower decile
Colorado River - Glenwood Springs	1	1813	1847	1983	1853	2332	2497	2531	1607
- near Cameo	2	1263	1200	1266	1344	1564	1665	1700	1044
Taylor River	3	127	142	143	130	164	175	177	123
Gunnison River - above Blue Mesa	4	789	861	891	927	1037	1133	1198	749
- Crystal reservoir	5	147	150	157	159	191	206	215	130
- near Grand Junction	6	874	848	871	1119	1172	1206	1224	737
Dolores River near Cisco	7	701	619	651	949	899	959	1044	538
Colorado River near Cisco	8	153	121	130	208	114	107	123	106
Green River - below Fontenelle Dam	9	1017	1246	1381	1201	1283	1488	1572	1084
- near Green River WY	10	27	75	89	46	83	103	105	65
- near Greendale UT	11	333	493	438	437	530	605	652	429
Yampa River near Maybell	12	1023	1037	1102	1060	1319	1395	1503	902
Little Snake River near Lily CO	13	357	422	432	436	430	540	572	367
Duchesne River near Randlett UT	14	625	760	727	723	755	934	1018	661
White River near Watson UT	15	487	474	528	523	669	641	651	413
Green River at Green River UT	16	305	381	443	391	465	519	565	332
San Rafael near Green River UT	17	147	143	158	185	164	219	252	124
San Juan River - near Archuleta NM	18	1121	989	884	1266	1284	1487	1654	861
- near Bluff UT	19	766	751	719	997	1148	1277	1383	653
Colorado River at Lee's Ferry AZ	20	414	411	395	547	551	682	720	358
Paria River at Lee's Ferry AZ	21	25	20	17	23	26	20	17	17
Little Colorado near Cameron AZ	22	210	162	122	214	272	186	185	141
Colorado River near Grand Canyon AZ	23	157	183	157	157	157	157	157	159
Virgin River at Littlefield AZ	24	185	142	145	211	199	223	267	123
Colorado River - below Hoover Dam	25	335	300	335	335	335	335	335	261
- below Davis Dam	26	33	160	97	-71	121	121	121	139
Bill Wiliams River below Alamo Dam	27	121	58	47	129	141	143	164	51
Colorado River - below Parker Dam	28	15	62	71	22	45	45	45	54
- above Imperial Dam	29	150	272	498	101	237	237	237	236
Upper Basin Total		12513	12989	13403	14525	16179	17858	18877	11300
River Total		13719	14328	14874	15623	17686	19304	20388	12464

All figures are net additions at the gauging station, measured in kaf/year.

[a] Synthetic flows constructed from tree ring data reported by Stockton (1975).
[b] Numbered gauging stations and net additions used by Colorado River Simulation System (USBR,1986b).

CHAPTER 8
MODEL RESULTS UNDER ALTERNATIVE INSTITUTIONAL SCENARIOS

Results of applying the estimated economic demands for basin water resources, request levels, and basin flows to the general model developed in the previous chapter are presented here. In the discussion below a unique specification of demand, request, and flow levels is termed a model definition. Six model definitions are considered, representing estimated demands and requests for 1990, 2010, and 2030 under two alternative flow levels. Each model definition includes the nine alternative institutional scenarios presented in Chapter 7. Scenarios range from rigid allocation based on Compact and state priorities reflecting existing water rights, to a scenario allowing water transfers maximizing total economic value across all consumptive and nonconsumptive uses for which economic demands were developed.

Results for 1990 demand and request levels, and the historic ten-year average lower decile flow level are discussed in detail. Other model results are then summarized. The chapter concludes with a discussion of the sensitivity of results to model assumptions.

Base Model Results: 1990 Demand, Lower Decile Flow

The base model definition uses 1990 water demand functions, 1990 request levels in non-modeled sectors, and the ten-year average lower decile flow level. The flow levels used for the base model run are the average annual reconstructed flows for years 1960 to 1969. Results presented for the base model definition include basin water allocation and economic impacts under each of the institutional scenarios presented in the Chapter 7. Table 8.1 summarizes solutions for the base model definition. Figure 8.1 shows estimated differences in water use resulting from the alternative water allocation institutions and the corresponding economic impacts. All economic sectors, including expanded agricultural sectors are included in calculation of economic impacts in Figure 8.1. The remainder of this section presents a discussion of the estimated allocation and economic impacts of the alternative institutional scenarios.

Group 1: Allocation in Compliance with Compact Priorities

Existing priorities, no water transfers. The request and flow levels used in the base model definition lead to a water deficit in the lower basin. Upper basin water requests are satisfied in full. Application of the priority system implicit in existing institutions (Scenario 1) governing interstate allocation of basin waters leads to significant curtailment of deliveries to MWD. Giving an assumed Central Arizona Project (CAP) diversion of 850 maf institutional preference over MWD diversions in excess of 520 kaf causes the Colorado Aqueduct to be limited to 260 kaf below capacity, or 1,040 kaf. Applying this strict priority system to the flow and request levels used in the base model definition gives a good representation of the present water year in the Colorado River basin. Actual CAP diversions of 800-900 kaf are anticipated, while MWD is expected to divert between 1,000 and 1,200 kaf (Schempp, 1990). The full water budget for the scenario is given in Table 8.2.

Salinity levels at each model node are calculated as an intrinsic part of CRIM. The base model definition and institutional priority scenario are used for salinity calibration. The major storage reservoirs are assumed to be salt sinks of unknown magnitude, calculated by the calibration. The calibration is accomplished by constraining salinity at Imperial Dam to 850 mg/l. This is the average level for 1968-1978 (Department of Interior, 1989), the most recent ten year period with average annual flows near that of the ten year average lower decile flow used in the base model. Additional salt sinks are not identified, with the exception of water exports from the basin. (Since typical return flows from the Gila River are zero, CAP diversions are also considered exports.) The importance of basin reservoirs as salt sinks is thus overstated by the model calibration. Table 8.3 gives the salt budget with water allocation by priority using the base model definition. A reduction of total salts by 700 ktons is found to result in a salinity concentration of 850 mg/l at Imperial Dam. This 700 kton salt sink is fixed with all additional institutional scenarios and models.

Table 8.1. Results by institutional scenario, base model (1990 demand and request levels, historic lower decile flow.)

Institutional Scenario	Upper Basin Use (maf)	Lower Basin Use (maf)	Annual Net Benefits from Colorado River Water: Total ($ million)	Consumptive Uses ($ million)	Hydropower Generation ($ million)	Salinity Damages ($ million)	Marginal Value of Water and Salinity: Upper Basin Water ($/af)	Lower Basin Water ($/af)	Upper Basin Salinity ($/ton)
1. Allocation by priority	2.315	6.354	1,365	1,076	389	(100)			
(modeled only)			1,223	932	389	(98)			
2. Use values (intrastate)[a]	2.315	6.354	1,434	1,169	389	(124)	1	20	0
(modeled only)			1,293	1,025	389	(121)			
3. Use values only[a]	2.301	6.368	1,437	1,169	390	(121)	19	20	0
(modeled only)			1,295	1,025	390	(119)			
4. Use values only[b]	2.161	6.501	1,453	1,170	396	(113)	18	19	0
5. Use & hydropower values[a]	2.265	6.402	1,446	1,168	391	(113)	65	20	0
(modeled only)			1,303	1,024	391	(113)			
6. Use & salinity values[a]	2.261	6.405	1,450	1,168	391	(109)	64	67	(48)
(modeled only)			1,306	1,023	391	(109)			
7. Use & hydropower values[b]	1.708	6.617	1,490	1,158	417	(85)	46	0	0
8. Use & salinity values[b]	1.629	6.546	1,500	1,151	421	(72)	51	53	(56)
9. Use, hydro, & salinity values[b]	1.555	6.561	1,503	1,148	424	(68)	96	52	(56)

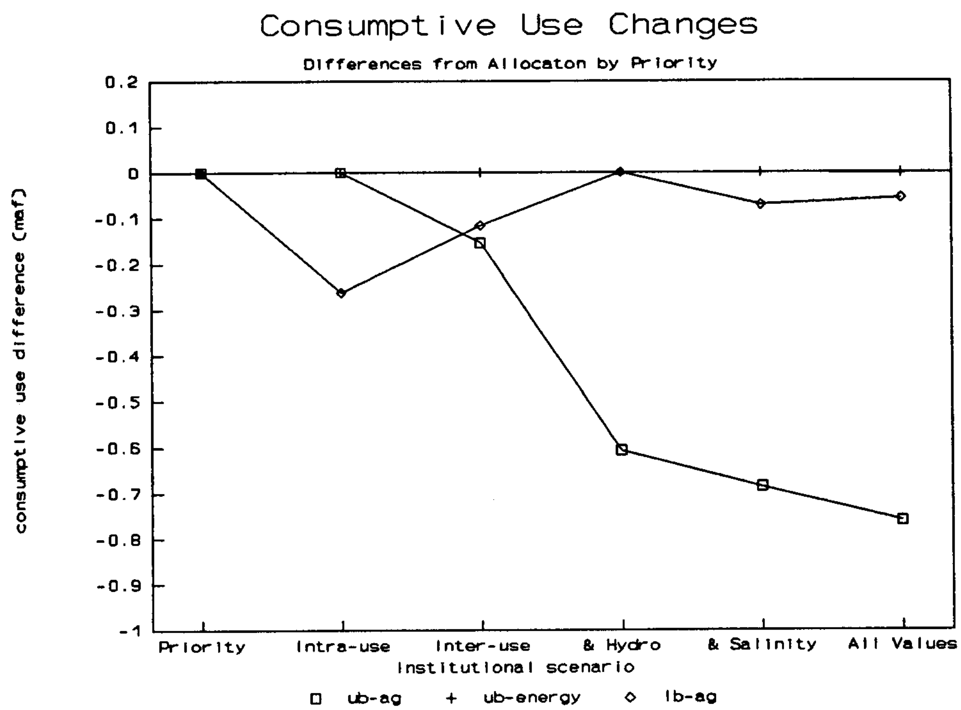
All figures are annual values.

Institutional scenarios are explicitly defined, by number, in Table 7.1.

Except for hydropower values, absolute levels of benefits and losses are only indicative; differences between alternative institutional scenarios should be given most consideration.

Upper basin marginal values are calulated at the Grand Valley;
Lower basin marginal water values are at the Colorado River Aqueduct
and include the value of salinity dilution where appropriate.

[a] Only explicitly modeled sectors included in objective function.
[b] Both modeled and expanded economic sectors included in objective function.



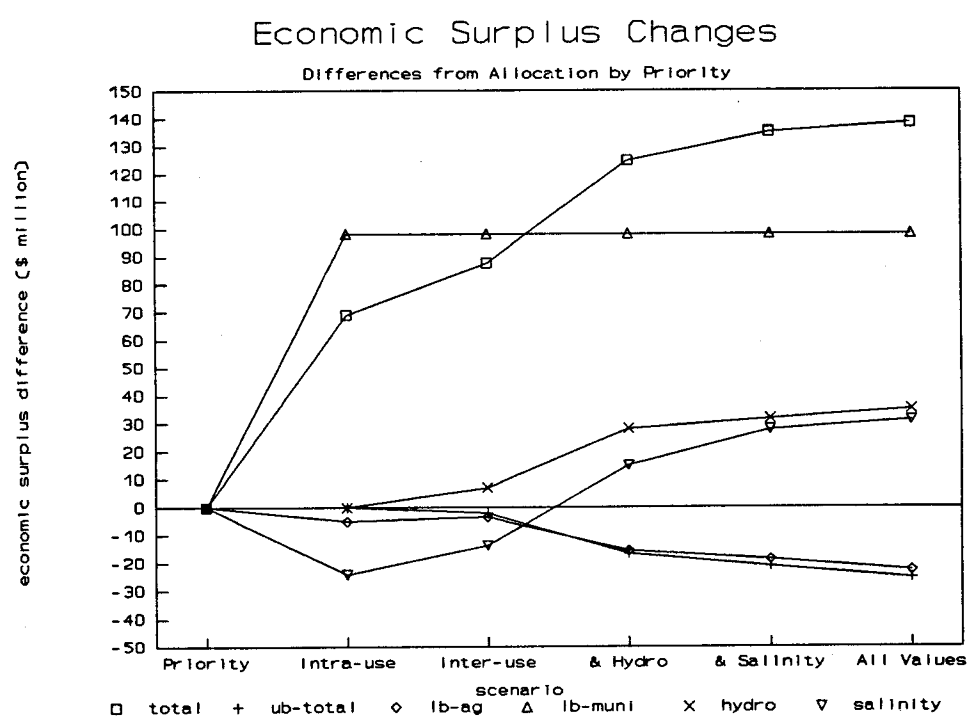


Figure 8.1. **Consumptive use and total surplus under Scenarios 1,2,4,7-9, respectively, base model (1990, historic lower decile flow.)**

Table 8.2. Water mass balance summary for base model (1990 demand and request levels, historic lower decile flow) and allocations by priority.

Demand Sectors	Flow Additions	Flow Adjustments[a]	Requests (not modeled)	Consumptive Use	Evaporation Losses	Main-stem Flow
Upper Green River	1,814		92	349		1,373
Yampa and White Rivers	1,932		165	13		3,127
Duchesne and San Rafael Rivers	903		124	647		3,259
Upper Colorado River	3,047		970	163		5,173
Gunnison River	1,858	381	84	396		6,933
Dolores River	740		48			7,625
San Juan River	1,740			747	575	8,618
Glen Canyon Dam		411	51			8,404
Paria River	241					8,646
Virgin River	142	345	49			9,083
Las Vegas		251	152		1,123	9,182
Hoover - Davis - Parker Dams		-164				7,895
Bill Williams River	58	160				8,113
Colorado River Aqueduct		62		1,037		7,138
CAP Diversion		-120		850		6,168
Colorado River Indian Reservation			333	398		5,437
Palo Verde Irrigation District				423		5,014
Imperial Irrigation District		271		2,640		2,646
Coachella Irrigation District				344		2,302
Yuma			125	662		1,515
Upper Basin Total	12,989[b]		1,534	2,315		
Lower Basin Total	1,338[b]		659	6,354		
Full Basin Total	14,327[b]		2,193	8,669	1,698	

All figures are annual values, expressed in kaf/year.

[a] Flow adjustments include minor consumptive uses, tributary flows, and channel gains and losses.
[b] Total includes flow adjustments for minor tributaries and channel gains and losses.

Table 8.3 **Salinity mass balance summary for base model (1990 demand and request levels, historic lower decile flow) and allocations by priority.**

Demand Sectors	Mainstem Flow (kaf)	Salt Loading (ktons)	Consumptive Use (kaf)	Salt Exports (ktons)	Mainstem Salinity (ktons)	Salinity Concentration (mg/l)
Upper Green River	1,373	1,113	441		1,113	597
Yampa and White Rivers	3,127	750	178	4	1,859	437
Duchesne and San Rafael Rivers	3,259	761	771		2,619	591
Upper Colorado River	5,173	410	1,133		3,326	473
Gunnison River	6,933	1,477	480		4,803	510
Dolores River	7,625	716		48	5,519	532
San Juan River	8,618	1,168	747		6,688	571
Glen Canyon Dam	8,404		51		6,688	585
Paria River	8,646				6,688	569
Virgin River	9,083	1,973	49		8,661	701
Las Vegas	9,182		152		8,661	694
Hoover-Davis-Parker Dams	7,895	-701[a]			7,960	742
Bill Williams River	8,113				7,960	722
Colorado River Aqueduct	7,138		1,037	1,009	6,951	716
CAP Diversion	6,168		850	842	6,109	728
Colorado River Indian Reservation	5,437		731		6,109	826
Palo Verde Irrigation District	5,014		423		6,109	896
Imperial Irrigation District	2,646		2,640	3,050	3,058	850
Coachella Irrigation District	2,302		344	397	2,661	850
Yuma	1,515		787		2,661	1,292
Upper Basin Total		6,396		4		
Lower Basin Total		1,272		5,299		
Full Basin Total		7,668		5,303		

All figures are annual values.

[a] Calibration number giving salinity concentration at Imperial Dam of 850 mg/l.

Return flows and salinity from Wellton-Mohawk Project users in Arizona are assumed by the model to return wholly to the River. Approximately 110 kaf per year of highly saline return flows from the Project[22] are in fact drained to the sea and are not included in deliveries to Mexico (U.S. Department of Interior, 1989). As a result, CRIM substantially overestimates the salinity of Mexican deliveries.

Total economic surplus from consumptive water uses, economic losses from salinity damages, and total benefits from hydropower production are calculated for each of the modeled and extended sectors under the resulting allocation. Since the demand functions used here (with the exception of demand for water for hydropower generation) are poorly defined or undefined at low use levels, no particular significance is attached to the levels calculated for this first institutional scenario. Differences between levels calculated in different scenarios are generally well-defined however, and are the basis for economic efficiency comparisons of institutional allocation rules. Total salinity losses are measured relative to reference salinity levels (800 mg/l for lower basin agriculture and 415 mg/l for the MWD service area); differences in levels between institutional scenarios are again of greatest interest. Table 8.4 shows economic surplus from consumptive uses, hydropower generation, and salinity impacts under the priority system allocation.

Intrastate Transfers. Water transfers within state boundaries do not require modifications to the basic agreements allocating basin water between states, and may provide significant economic benefits in the face of supply shortages in the basin. Allowing intrastate transfers which maximize economic surplus from consumptive water uses (Scenario 2) results in a significant water transfer between MWD and the Imperial Valley. The shortage of 260 kaf experienced by MWD under the strict priority system (Scenario 1) is

[22] The high salinity concentration of Wellton-Mohawk drainage water is the result of both concentration, and the high salinity level of an underlying aquifer.

Table 8.4. Summary of economic benefits of Colorado River use for base model (1990 demand and request levels, historic lower decile flow) and allocations by priority.

Demand Sectors	Consumptive Use (kaf)	Diversions (kaf)	Consumptive Use Benefits ($ million)	Hydropower Benefits ($ million)	Salinity Damages ($ million)
Upper Green River	349	658	6		
Yampa and White Rivers	13	13	18		
Duchesne and San Rafael Rivers	647	1135	11		
Upper Colorado River	163	326	3		
Gunnison River	396	792	7		
San Juan River	747	1186	12		
Glen Canyon Dam		8404		135	
Hoover - Davis - Parker Dams		7895		254	
Colorado River Aqueduct	1037	1037	799		-91
CAP Diversion	850	850			
Colorado River Indian Reservation	398	663	25		2
Palo Verde Irrigation District	423	846	27		-1
Imperial Irrigation District	2640	2640	112		-7
Coachella Irrigation District	344	344	15		-1
Yuma	662	1068	42		-2
Upper Basin Total - all sectors	2315		57	135	
- modeled only	176		21	135	
Lower Basin Total - all sectors	6354		1,019	254	-100
- modeled only	3677		911	254	-98
Full Basin Total - all sectors	8669		1,076	389	-100
- modeled only	3853		932	389	-98

All figures are annual values.
Agricultural salinity damages are calculated relative to a 800 mg/l reference; municipal salinity damages assume alternative supplies have salinity levels of 415 mg/l.

transferred to the Imperial Valley under this scenario. Because economic costs of the shortage are significantly reduced by the transfer, net economic surplus is increased. The marginal value of lower basin water under this scenario is $20/af, reflecting the marginal value of water in the Imperial Valley after the water transfer. The net economic value of consumptive uses increases by $93 million, or $360/af of transferred water. If the increase in salinity damages incurred by MWD water users is included, the net value of the transfer declines to $69 million, or $260/af. The large surplus is generated by satisfaction of the very high marginal benefits in municipal water use. It is interesting to note that the recently completed agreement between MWD and the Imperial Irrigation District for transfer of 100,000 kaf has an implicit cost of $128/af to MWD (Quinn, 1990). The model result here is consistent with this agreement, showing that MWD has an economic incentive to purchase additional supplies of Colorado River water, and that Imperial Valley irrigators could realize significant benefits in the transaction. Additional talks are underway between MWD and both Imperial and Palo Verde Irrigation Districts, and development of technology for lining of the All-American canal is underway (Quinn).

Group 2: Interstate Transfers for Consumptive Uses

Interstate water transfers would probably require significant institutional change in the framework governing Colorado River water allocation. Such change could be stimulated by persuasive evidence that significant economic benefits could be achieved by allowing interstate transfers. Model runs for 1990 demand levels do not show this to be the case if only consumptive use values are considered, given the existing possibility for intrastate transfers.

The most restrictive institutional scenario allowing interstate transfers includes only consumptive use values, with agricultural demands limited to the explicitly modeled demand sectors (Grand and Imperial Valleys). The model solution in this case (Scenario 3) shows a water transfer of 14 kaf from upper to lower basins compared to Scenario 2 which allowed only intrastate water transfers. The upper basin reduction is from 163 kaf to 149 kaf in Grand Valley agriculture; water use in fossil fuel based energy production is virtually unchanged. MWD continues to receive full deliveries, while Imperial Valley diversions increase by 14 kaf over the intrastate scenario solution. The economic surplus gain from consumptive uses over that with only intrastate transfers (Scenario 2) is $110,000, or about $8/af of transferred water. If the value of hydropower production and salinity damage reductions are included, however, these figures rise dramatically to $3.2 million, or $230/af. Marginal water values (based on consumptive uses only) are $19/af in the upper basin and $20/af in the lower basin. The difference reflects evaporation losses in transporting water from the upper to lower basin.

Scenario 4 includes only consumptive use values but adds agricultural sectors not explicitly modeled in Chapter 3. In these additional sectors demand functions are inferred from their similarity to the Grand Valley or Imperial Valley. Upper basin agricultural regions are not assumed to be net salt producers, however. In this scenario upper basin use declines by 150 kaf over the full request level, with the reductions distributed across agricultural areas with full requests of 2300 kaf. Upper and lower basin marginal water values decline slightly to $18 and $19/af, respectively, as proportionate supply reductions in agricultural sectors are reduced.

The basinwide transfers necessary to give the water allocation estimated under Scenario 4 would result in a net economic surplus in consumptive use of $1 million over that possible with only intrastate water transfers (Scenario 2). If hydropower benefits of $7 million, and reduced salinity damages of $10 million are added however, net economic surplus across all modeled values is $18 million for the 154 kaf of transferred upper basin water, or $120/af. (This unit value is substantially below that in the previous scenario because most upper basin users are not considered salt producers here.) Thus marginal benefits of allowing interstate water transfers in the Colorado River basin could be very significant, though the total amounts transferred under markets considering only consumptive uses might be small.

The results presented to this point illustrate several fundamental conclusions of this study. First, water transfers from agriculture to MWD produce substantial economic benefits. This is expected given the difference in marginal water values in agricultural compared to municipal water uses. Second, there is very limited motivation for interstate water transfers based on consumptive use values alone. Upper to lower basin transfers, were they to actually occur, would likely take place directly between agricultural and municipal users. Such transfers could alternatively be viewed, however, as transfers between upper basin and lower basin agricultural users if municipal use is constant. Because the differences in consumptive use values are modest between these users, any gains from trade would be equally modest. The analysis in Chapter 3 suggests that marginal values are higher in lower basin agriculture than upper basin agriculture. Given the uncertainty in measurement of agricultural water values, however, this research cannot give a firm conclusion as to the direction of such transfers, even in the hypothesized absence of significant institutional constraints on transfers based on consumptive use values. Despite this uncertainty, if agricultural water demand elasticities are not too high, then the size of such transfers would be relatively small, as shown in the above model results.

Water values in consumptive uses are only one part of the value of Colorado River water, however. The above results show clearly that substantial economic benefits occur from increased hydropower generation and salinity damage reductions as a consequence of transfers from upper to lower basins motivated by consumptive use values. Inclusion of these values in estimating allocatively efficient water transfers is considered in the next section.

Group 3: Scenarios Incorporating Nonconsumptive Use Values

The magnitude of nonconsumptive use values in upper to lower basin transfers given above suggests that inclusion of these values in a water market would result in significant upper to lower basin transfers. Model results confirm that large transfers are in fact economic efficiency improvements when more complete sets of values are considered.

Considering institutional scenarios with only modeled sectors initially (agricultural sectors including only Grand and Imperial Valleys), inclusion of either hydropower benefits (Scenario 5) or salinity damages (Scenario 6) in the model results in transfers from the Grand Valley of 50 kaf and 54 kaf, respectively. The latter figure represents 33 percent of Grand Valley requests, the maximum transfer allowed by the model; further transfers might well be expected, but are not considered here because they extend below the valid range for Grand Valley water use presented in Chapter 3. Results of these two scenarios may thus be artificially similar, given that the level of transfers from the Grand Valley presented here is a lower bound.

Changes in economic surplus are given relative to Scenario 2 allowing only intrastate transfers. Net surplus gains, measured over both consumptive and nonconsumptive use values, are $12 million and $16 million for Scenarios 5 and 6 including hydropower and salinity reduction values, respectively.

In Scenario 5 which includes only consumptive use and hydropower values, there is actually a loss of $0.7 million from consumptive uses, but gains of $2.3 million and $10 million from hydropower and salinity reduction benefits, respectively. The marginal value of upper basin and lower basin water (now including opportunity costs in consumptive use and hydropower production) is $65 and $20/af, respectively. The lower basin marginal value is measured downstream of all assumed hydropower production, but above all economic demands for consumptive uses. The difference reflects the value of upper basin water for hydropower production ($46/af) minus the loss from evaporation ($1/af).

For Scenario 6 including losses from salinity damages but not including hydropower values, the reduction in consumptive use benefits increases to $1.5 million, while the gains from hydropower production and salinity reduction are $2.5 million and $15 million, respectively. The upper basin marginal water value is $64/af and the lower basin marginal value is $67/af. These values include approximately $20/af for consumptive uses, with the balance for salinity dilution. Again, evaporation losses account for the difference in upper and lower basin values. Because salinity losses are included in the objective function, marginal values of salt loading are also derived. The marginal value of salinity loading, taken upstream of all basin water users suffering salinity damages, is $48/af.

Similar results are found if the additional upper and lower basin agricultural demand sectors are added to the above scenario definitions. Inclusion of hydropower values with the full set of upper basin agricultural demands (Scenario 7) results in reductions in upper basin use of 610 kaf, or 26 percent of modeled requests. Inclusion of salinity values in the institutional scenario (Scenario 8) gives reductions in upper basin use of 690 kaf, or 30 percent of modeled requests. The proportional reduction across upper basin agricultural users here is somewhat below that for the Grand Valley only since salinity production in other upper basin sectors is not assumed. Reductions in upper basin consumptive uses are, by definition, beneficial in reducing salinity damages only through increases in dilution. Because significant salinity production does occur in upper basin agriculture outside the Grand Valley and is not included here, the estimated level of water transfers represents an underestimate of those that could occur with an interstate market including salinity reduction values.

Economic surplus changes for Scenario 7 which includes consumptive use and hydropower values (measured relative to that in Scenario 2 with intrastate transfers only) gives a surplus loss of $11 million for consumptive uses, but surplus gains of $28 million in hydropower production and $39 million for salinity reduction, for a net gain of $56 million. This gives average net benefits of $92/kaf for the transfer of 610 kaf. The marginal value of upper basin water rises to $46/af, the value of hydropower production. Since water quantity is not constraining and water quality is not considered in this optimization, the marginal value of lower basin water is zero.

The comparable figures for Scenario 8 (consumptive use plus salinity reduction values), are a surplus loss of $18 million for consumptive uses, and surplus gains of $32 million in hydropower production and $52 million for salinity reduction, a net gain of $66 million. The average net benefit for the 690 kaf transfer is $95/af. Marginal values of upper and lower basin water are $51 and $53/af, respectively, the value of water for dilution. The marginal value of salinity loads is -$56/ton.

Significantly, the Mexican delivery constraint is not binding when hydropower or salinity losses are included in scenarios with most upper basin agricultural demand sectors. This result occurs because the assumed maximum (or near maximum) deliveries to lower basin consumptive uses are made, while the marginal value of water for consumptive uses in agriculture in the upper basin remains below the benefits from both hydropower production and salinity reduction.

Scenario 9 is the most comprehensive of those presented in this research. It includes values for consumptive uses, hydropower production, and salinity reduction. Both directly modeled sectors, and extensions to most upper and lower basin agricultural demand sectors are included. Results of this comprehensive optimization are very similar to those found above with inclusion of either hydropower or salinity damage values only. The similarity is somewhat artificial because the level of transfers from upper basin demand sectors is constrained to 33 percent of requests. Again, this limit is imposed because the upper basin demand functions are not well-defined past this level of reduction. The level of transfers is 760 kaf, or 33 percent of the included agricultural demand, the upper limit allowed by the model. Net benefits in all sectors over those with just intrastate transfers increase by $69 million, or $91/af of transferred upper basin water. Upper basin transfers again exceed the needs of lower basin sectors' consumptive use requests, leading to deliveries to Mexico in excess of 1,515 kaf. The marginal value of upper basin water is $96/af, of which $50/af is the value of salinity dilution. The marginal value of salinity loads is -$56/ton.

It is instructive to look in detail at the solution for Scenario 9. Table 8.5 shows use in economic demand sectors, and marginal water and salinity loading values at each sector. Upper basin agricultural demands are at their constrained lower limit, but water use for fossil fuel based energy demands is very near its upper limit, or request level. Because the Mexican delivery constraint is not binding, lower basin water is valued only for salinity dilution. The optimal allocation shows small reductions from request levels on the Colorado River Indian Reservation and Palo Verde Irrigation District; the water saved is more valuable for salinity dilution benefits to downstream irrigators than for consumptive use at the margin. Imperial Valley and Coachella diversions are exports, and thus do not affect salinity concentrations directly. Yuma diversions are assumed unconstrained by downstream interests. The latter three economic demands are satisfied in full up to their request levels. If salinity levels in deliveries to Mexico were considered, then an allocatively efficient solution might include reductions in consumptive use Yuma area irrigators.

Table 8.5. Summary of marginal economic values for base model (1990 demand and request levels, historic lower decile flow) and allocations optimizing total economic benefits.

Demand Sectors	Consumptive Use (kaf)	Mainstem Flow (kaf)	Mainstem Salinity (ktons)	Salinity Concentration (mg/l)	Marginal Water Value ($/af)	Marginal Salinity Value ($/ton)
Upper Green River	234	1,488	1,113	550	96	(55)
Yampa and White Rivers	13	3,243	1,859	422	96	(56)
Duchesne and San Rafael Rivers	433	3,588	2,619	537	96	(56)
Upper Colorado River	109	5,556	3,129	414	96	(56)
Gunnison River	265	7,446	4,606	455	96	(56)
San Juan River	500	9,378	6,491	509	96	(56)
Glen Canyon Dam		9,144	6,491	522	96	(56)
Hoover - Davis - Parker Dams		8,621	7,763	662	83	(56)
Colorado River Aqueduct	1,300	7,601	6,629	641	52	
CAP Diversion	850	6,631	5,876	652	29	(32)
Colorado River Indian Reservation	370	5,928	5,876	729	32	(29)
Palo Verde Irrigation District	395	5,533	5,876	781	30	(26)
Imperial Irrigation District	2,640	3,165	3,204	745	26	(15)
Coachella Irrigation District	344	2,821	2,856	745	15	(12)
Yuma	662	2,034	2,856	1,033	12	

All figures are annual values.
Based on results for Scenario 9, including the value of hydropower production and reductions in salinity damages.

<u>Summary</u>

The maximum economic benefit achievable through water transfers of Colorado River basin water, relative to allocations by existing priorities, is estimated at $140 million. This is composed of gains of $74 million for consumptive uses, $35 million for hydropower generation, and a reduction in salinity damages of $31 million. Such a transfer would be almost entirely from upper basin agriculture. The average net benefit of the transfer is $185/af. Mexican users would also benefit from increased water deliveries and salinity reductions. For comparison, allowing only intrastate transfers between MWD and the Imperial Valley (Scenario 2, under this particular model definition) gives net gains over existing allocation priorities estimated at $69 million; the net consumptive use gain is $98 million, but salinity damages increase $24 million as more

Colorado River water is used for municipal purposes. There would be minimal impacts to hydropower generation and Mexican deliveries. The average net benefit of transferring 260 kaf between these users, including salinity impacts, is $265/af.

Additional Model Definitions

Five additional model definitions are examined in this section. Two use the historic ten-year average lower decile flow levels with future (year 2010 and 2030) demand and request levels. The remaining three models use corresponding lower decile synthetic flow levels based on upper basin flows for the period 1564 to 1961 reconstructed from tree ring data (Stockton, 1975). These models could be considered representative of an extreme drought if average annual flows are 14 maf or above at Lee's Ferry, or of more typical dry conditions if average annual flows are near 13 maf. The synthetic ten-year average lower decile flow level at Lee's Ferry is 11.3 maf, compared to 13.0 maf for the historic lower decile level. For convenience, the flow level of 13.0 maf annually is termed "dry" while a flow of only 11.3 maf is termed a "drought" condition. Use of demand and request levels for 1990, 2010, and 2030 distinguish the latter three models.

The six total models can be roughly ordered from greatest to smallest supplies relative to demands and requests. The models thus simulate conditions of increasing resource scarcity. Table 8.6 summarizes impacts of alternative allocation institutions with the six model definitions. Summaries of individual model results are presented in Tables 8.7 - 8.11 and Figures 8.2 - 8.6.

Group 1: Allocation in Compliance with Compact Priorities

Existing priorities, no water transfers. If anticipated upper basin water development proceeds, shortfalls are likely during both "dry" and "drought" periods if average annual delivery of 8.25 maf to the lower basin is upheld. There are, however, significant questions about the impact of Indian water rights on Compact entitlements, and on the level of Mexican deliveries during drought. The discussion that follows assumes that Indian water rights fall within the Compact (or, more likely and equivalently for purposes here, are counted against states rights under the Compact) and that Mexican deliveries are fixed at 1.5 maf annually.

Two distinct patterns of water shortfalls emerge. Under "dry" conditions upper basin shortfalls are expected to remain relatively modest to the year 2030. Lower basin agriculture (under present institutional allocation and water rights) would be largely unaffected, but MWD would lose approximately 800 kaf of presently surplus water. In addition, the Central Arizona Project would experience significantly lower deliveries in 2010 and 2030 than the scheduled 1,500 kaf. Under "drought" conditions the lower basin is no worse off than under "dry" conditions because it is protected by the Lee's Ferry delivery constraint. Because CRIM allows increased flexibility in drawing down reservoirs, plus gains from lower evaporation at Lake Mead, in "drought" conditions lower basin water users actually receive slightly increased supplies over comparable "dry" condition models. The upper basin is much worse off under the low flows of the "drought" models. This is anticipated since the delivery requirement at Lee's Ferry in effect provides lower basin users with senior rights. Under the extreme conditions simulated by "drought" flow levels, the junior rights of the upper basin could suffer a shortfall of 1,100 kaf under 1990 assumed request levels. Shortfalls increase to over 2,000 kaf, or 45 percent of total requests by 2030 if assumed development occurs.

Intrastate Transfers. Significant economic efficiency gains are possible if intrastate transfers occur (Scenario 2). Such transfers would be an extension of present water transfer activity within state boundaries, and would not affect Compact allocations or priorities. It is assumed that such within-state transfers would be motivated only by consumptive use benefits; salinity impacts are not included in the optimization. Increasing levels of such transfers, though likely not to the extent predicted in model solutions here, are considered probable. Efficiency gains of over $500 million, dominated by the value of maintaining municipal supplies for MWD, are predicted for the future. If alternative low cost additional supplies are available to southern California urban areas then the gains from intrastate transfers of Colorado River water could be more modest. Water shortfalls in upper basin energy development resulting from Compact obligations are assumed to be met from within state agricultural users in this scenario. Given presently anticipated levels of water development for agricultural use and energy production, the marginal value of upper basin water is

Table 8.6. Performance of alternative water allocation institutions under differing flow and demand levels.

	Allocation by Compact Priorities						Allocation Allowing Only Intrastate Transfers[a]		Allocation Allowing Interstate Transfers (By Consumptive Use Values Only)[b]			Allocation Allowing Interstate Transfers (Including Hydro and Salinity Values)[c]		
Model Definition[d]	Upper Basin Shortfall (kaf)	Upper Basin Shortfall (%)	MWD Surplus Shortfall (kaf)	MWD Surplus Shortfall (%)	CAP Shortfall (kaf)	CAP Shortfall (%)	All Values ($ million)	Consumptive Use Values Only ($ million)	Upper Basin Use (kaf)	All Values ($ million)	Consumptive Use Values Only ($ million)	Upper Basin Use (kaf)	All Values ($ million)	Consumptive Use Values Only ($ million)
1990, historic	0	0	263	34	0	0	69	93	-154	88	94	-760	138	72
2010, historic	489	10	803	100	688	46	558	656	8	560	657	-624	634	643
2030, historic	763	15	803	100	1050	70	690	800	138	673	802	-483	754	787
1990, synthetic	1,082	28	424	54	0	0	132	172	409	93	178	-245	159	161
2010, synthetic	1,978	42	803	100	727	48	576	675	693	513	693	-208	604	662
2030, synthetic	2,254	45	803	100	1089	73	718	831	800	637	855	-176	744	819

All figures are annual values.

[a] Scenario 2; figures are differences from allocations determined by Compact priorities (Scenario 1).
[b] Scenario 4; figures are differences from allocations determined by Compact priorities (Scenario 1).
[c] Scenario 9; figures are differences from allocations determined by Compact priorities (Scenario 1).
[d] Model definitions use ten-year average lower decile flow levels for each set of estimated annual virgin flows.

Table 8.7. Summary of institutional scenarios for model 2 (2010 demand and request levels, historic lower decile flow.)

Institutional Scenario	Upper Basin Use (maf)	Lower Basin Use (maf)	Annual Net Benefits from Colorado River Water: Total ($ million)	Consumptive Uses ($ million)	Hydropower Generation ($ million)	Salinity Damages ($ million)	Marginal Value of Water and Salinity: Upper Basin Water ($/af)	Lower Basin Water ($/af)	Upper Basin Salinity ($/ton)
1. Allocation by priority	2.568	6.086	1,265	974	366	(76)			
(modeled only)			1,119	825	366	(71)			
2. Use values (intrastate)[a]	2.568	6.086	1,823	1,630	366	(173)	30	30	0
(modeled only)			1,679	1,480	366	(167)			
3. Use values only[a]	2.569	6.085	1,823	1,630	366	(173)	29	30	0
(modeled only)			1,679	1,480	366	(167)			
4. Use values only[b]	2.576	6.078	1,825	1,631	365	(172)	23	24	0
5. Use & hydropower values[a]	2.534	6.118	1,833	1,629	367	(163)	74	29	0
(modeled only)			1,688	1,480	367	(159)			
6. Use & salinity values[a]	2.534	6.118	1,837	1,629	367	(159)	83	87	(59)
(modeled only)			1,691	1,479	367	(155)			
7. Use & hydropower values[b]	1.945	6.681	1,887	1,619	395	(127)	65	20	0
8. Use & salinity values[b]	1.946	6.680	1,899	1,617	395	(113)	69	72	(68)
9. Use, hydro, & salinity values[b]	1.944	6.682	1,899	1,617	395	(113)	115	72	(68)

All figures are annual values.

Institutional scenarios are explicitly defined, by number, in Table 7.1.

Except for hydropower values, absolute levels of benefits and losses are only indicative; differences between alternative institutional scenarios should be given most consideration.

Upper basin marginal values are calulated at the Grand Valley;
Lower basin marginal water values are at the Colorado River Aqueduct
and include the value of salinity dilution where appropriate.

[a] Only explicitly modeled sectors included in objective function.
[b] Both modeled and expanded economic sectors included in objective function.

Table 8.8. Summary of institutional scenarios for model 3 (2030 demand and request levels, historic lower decile flow.)

Institutional Scenario	Upper Basin Use (maf)	Lower Basin Use (maf)	Annual Net Benefits from Colorado River Water: Total ($ million)	Annual Net Benefits from Colorado River Water: Consumptive Uses ($ million)	Annual Net Benefits from Colorado River Water: Hydropower Generation ($ million)	Salinity Damages ($ million)	Marginal Value of Water and Salinity: Upper Basin Water ($/af)	Marginal Value of Water and Salinity: Lower Basin Water ($/af)	Marginal Value of Water and Salinity: Upper Basin Salinity ($/ton)
1. Allocation by priority	2.494	6.030	1,388	1,109	364	(86)			
(modeled only)			1,246	963	364	(81)			
2. Use values (intrastate)[a]	2.494	6.030	2,078	1,909	364	(195)	50	29	0
(modeled only)			1,938	1,763	364	(189)			
3. Use values only[a]	2.516	6.009	2,071	1,909	363	(201)	28	29	0
(modeled only)			1,932	1,763	363	(194)			
4. Use values only[b]	2.632	5.898	2,061	1,911	357	(208)	24	25	0
5. Use & hydropower values[a]	2.475	6.048	2,085	1,909	365	(189)	73	28	0
(modeled only)			1,943	1,762	365	(184)			
6. Use & salinity values[a]	2.476	6.048	2,089	1,908	365	(183)	90	94	(66)
(modeled only)			1,947	1,761	365	(179)			
7. Use & hydropower values[b]	2.013	6.490	2,128	1,900	386	(158)	66	21	0
8. Use & salinity values[b]	2.013	6.490	2,142	1,896	386	(140)	90	94	(76)
9. Use, hydro, & salinity values[b]	2.011	6.492	2,142	1,896	386	(140)	136	94	(76)

All figures are annual values.

Institutional scenarios are explicitly defined, by number, in Table 7.1.

Except for hydropower values, absolute levels of benefits and losses are only indicative; differences between alternative institutional scenarios should be given most consideration.

Upper basin marginal values are calulated at the Grand Valley;
Lower basin marginal water values are at the Colorado River Aqueduct
and include the value of salinity dilution where appropriate.

[a] Only explicitly modeled sectors included in objective function.
[b] Both modeled and expanded economic sectors included in objective function.

Table 8.9. Summary of institutional scenarios for model 4 (1990 demand and request levels, synthetic lower decile flow.)

Institutional Scenario	Upper Basin Use (maf)	Lower Basin Use (maf)	Annual Net Benefits from Colorado River Water: Total ($ million)	Annual Net Benefits from Colorado River Water: Consumptive Uses ($ million)	Annual Net Benefits from Colorado River Water: Hydropower Generation ($ million)	Salinity Damages ($ million)	Marginal Value of Water and Salinity: Upper Basin Water ($/af)	Marginal Value of Water and Salinity: Lower Basin Water ($/af)	Marginal Value of Water and Salinity: Upper Basin Salinity ($/ton)
1. Allocation by priority	1.664	6.193	1,252	975	364	(87)			
(modeled only)			1,128	848	364	(85)			
2. Use values (intrastate)[a]	1.664	6.193	1,384	1,147	364	(127)	49	22	0
(modeled only)			1,261	1,021	364	(124)			
3. Use values only[a]	1.697	6.162	1,377	1,148	363	(133)	21	22	0
(modeled only)			1,255	1,021	363	(128)			
4. Use values only[b]	2.073	5.803	1,345	1,153	345	(153)	23	24	0
5. Use & hydropower values[a]	1.663	6.195	1,386	1,147	364	(125)	67	22	0
(modeled only)			1,262	1,020	364	(122)			
6. Use & salinity values[a]	1.650	6.207	1,391	1,146	365	(119)	66	70	(48)
(modeled only)			1,266	1,019	365	(117)			
7. Use & hydropower values[b]	1.425	6.422	1,401	1,138	375	(112)	65	19	0
8. Use & salinity values[b]	1.444	6.404	1,410	1,137	374	(101)	63	66	(59)
9. Use, hydro, & salinity values[b]	1.419	6.427	1,411	1,136	375	(100)	106	62	(59)

All figures are annual values.

Institutional scenarios are explicitly defined, by number, in Table 7.1.

Except for hydropower values, absolute levels of benefits and losses are only indicative; differences between alternative institutional scenarios should be given most consideration.

Upper basin marginal values are calulated at the Grand Valley;
Lower basin marginal water values are at the Colorado River Aqueduct
and include the value of salinity dilution where appropriate.

[a] Only explicitly modeled sectors included in objective function.
[b] Both modeled and expanded economic sectors included in objective function.

Table 8.10. Summary of institutional scenarios for model 5 (2010 demand and request levels, synthetic lower decile flow.)

Institutional Scenario	Upper Basin Use (maf)	Lower Basin Use (maf)	Annual Net Benefits from Colorado River Water			Salinity Damages ($ million)	Marginal Value of Water and Salinity		
			Total ($ million)	Consumptive Uses ($ million)	Hydropower Generation ($ million)		Upper Basin Water ($/af)	Lower Basin Water ($/af)	Upper Basin Salinity ($/ton)
1. Allocation by priority	1.670	6.047	1,204	913	360	(69)			
(modeled only)			1,094	801	360	(66)			
2. Use values (intrastate)[a]	1.670	6.047	1,780	1,588	360	(167)	71	30	0
(modeled only)			1,677	1,479	360	(162)			
3. Use values only[a]	1.753	5.967	1,767	1,590	356	(180)	32	33	0
(modeled only)			1,662	1,478	356	(172)			
4. Use values only[b]	2.363	5.385	1,717	1,606	328	(217)	34	36	0
5. Use & hydropower values[a]	1.718	6.001	1,778	1,590	357	(169)	77	32	0
(modeled only)			1,671	1,477	357	(164)			
6. Use & salinity values[a]	1.690	6.028	1,785	1,588	359	(161)	85	89	(59)
(modeled only)			1,677	1,475	359	(157)			
7. Use & hydropower values[b]	1.688	6.030	1,781	1,590	359	(167)	70	24	0
8. Use & salinity values[b]	1.463	6.245	1,808	1,575	369	(137)	87	91	(70)
9. Use, hydro, & salinity values[b]	1.462	6.246	1,808	1,575	369	(137)	133	91	(70)

All figures are annual values.

Institutional scenarios are explicitly defined, by number, in Table 7.1.

Except for hydropower values, absolute levels of benefits and losses are only indicative; differences between alternative institutional scenarios should be given most consideration.

Upper basin marginal values are calulated at the Grand Valley;
Lower basin marginal water values are at the Colorado River Aqueduct and include the value of salinity dilution where appropriate.

[a] Only explicitly modeled sectors included in objective function.
[b] Both modeled and expanded economic sectors included in objective function.

Table 8.11. Summary of institutional scenarios for model 6 (2030 demand and request levels, synthetic lower decile flow.)

Institutional Scenario	Upper Basin Use (maf)	Lower Basin Use (maf)	Annual Net Benefits from Colorado River Water: Total ($ million)	Consumptive Uses ($ million)	Hydropower Generation ($ million)	Salinity Damages ($ million)	Marginal Value of Water and Salinity: Upper Basin Water ($/af)	Lower Basin Water ($/af)	Upper Basin Salinity ($/ton)
1. Allocation by priority	1.622	5.991	1,312	1,031	358	(77)			
(modeled only)			1,208	924	358	(74)			
2. Use values (intrastate)[a]	1.622	5.991	2,030	1,862	358	(190)	77	29	0
(modeled only)			1,934	1,761	358	(185)			
3. Use values only[a]	1.741	5.877	2,010	1,867	352	(209)	31	32	0
(modeled only)			1,912	1,760	352	(200)			
4. Use values only[b]	2.422	5.227	1,949	1,886	321	(257)	35	37	0
5. Use & hydropower values[a]	1.701	5.915	2,023	1,866	354	(197)	76	31	0
(modeled only)			1,923	1,759	354	(190)			
6. Use & salinity values[a]	1.664	5.951	2,034	1,864	356	(186)	91	96	(67)
(modeled only)			1,932	1,757	356	(181)			
7. Use & hydropower values[b]	1.738	5.880	2,022	1,869	352	(200)	70	25	0
8. Use & salinity values[b]	1.448	6.157	2,056	1,850	366	(160)	95	99	(77)
9. Use, hydro, & salinity values[b]	1.446	6.159	2,056	1,850	366	(160)	141	99	(77)

All figures are annual values.

Institutional scenarios are explicitly defined, by number, in Table 7.1.

Except for hydropower values, absolute levels of benefits and losses are only indicative; differences between alternative institutional scenarios should be given most consideration.

Upper basin marginal values are calulated at the Grand Valley;
Lower basin marginal water values are at the Colorado River Aqueduct
and include the value of salinity dilution where appropriate.

[a] Only explicitly modeled sectors included in objective function.
[b] Both modeled and expanded economic sectors included in objective function.

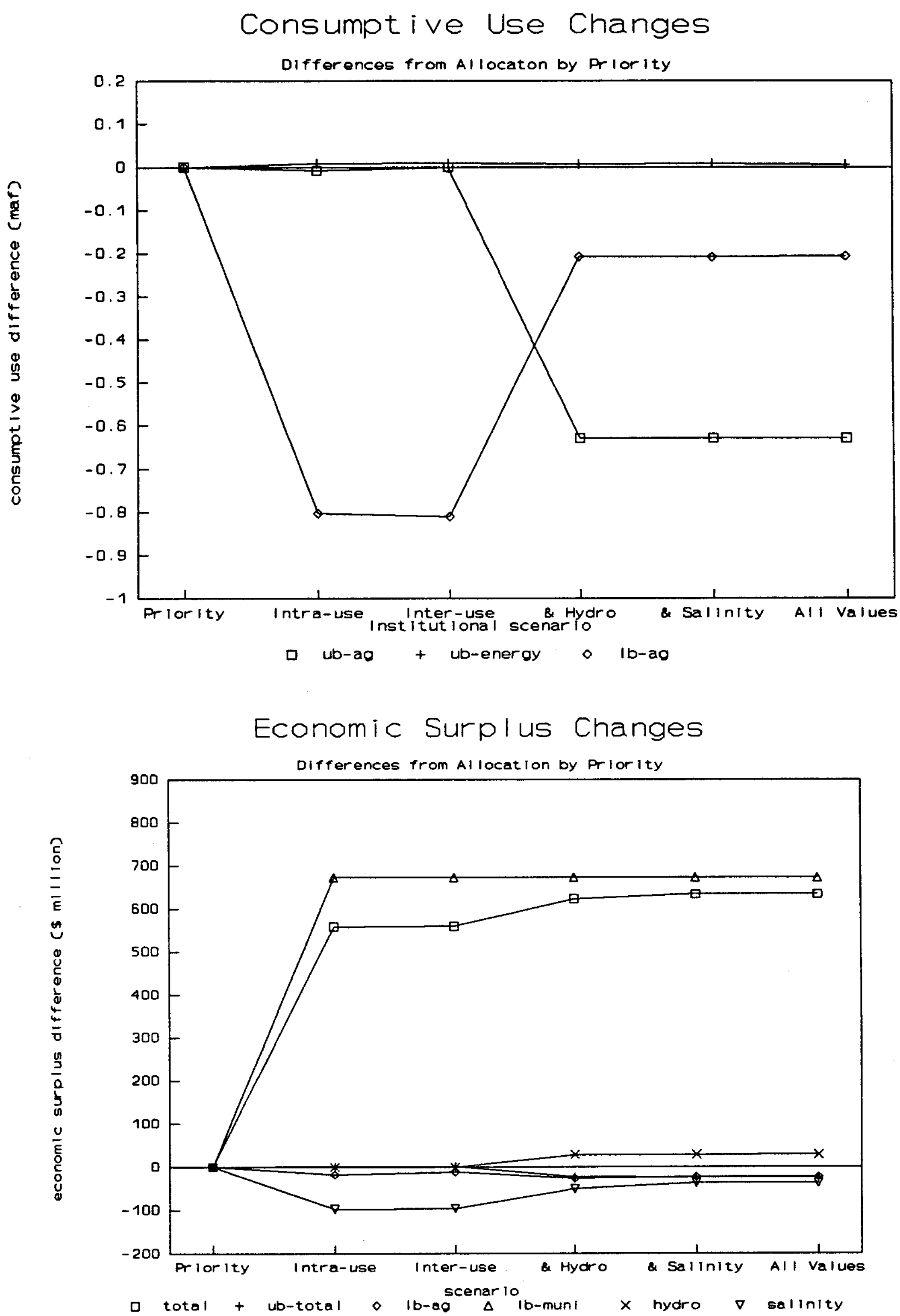


Figure 8.2. **Consumptive use and total surplus under Scenarios 1,2,4,7-9, respectively, year 2010 and historic lower decile flow.**

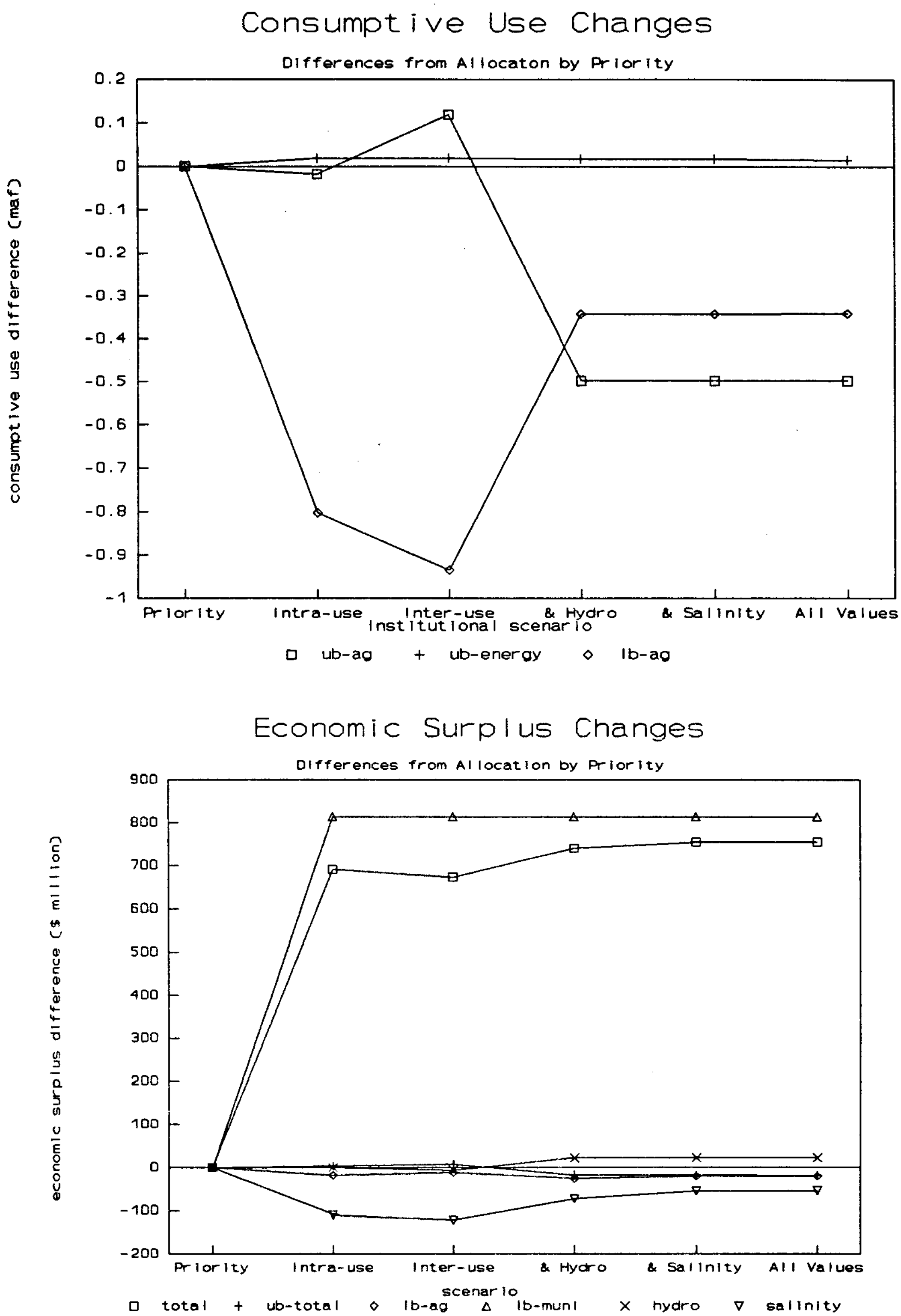
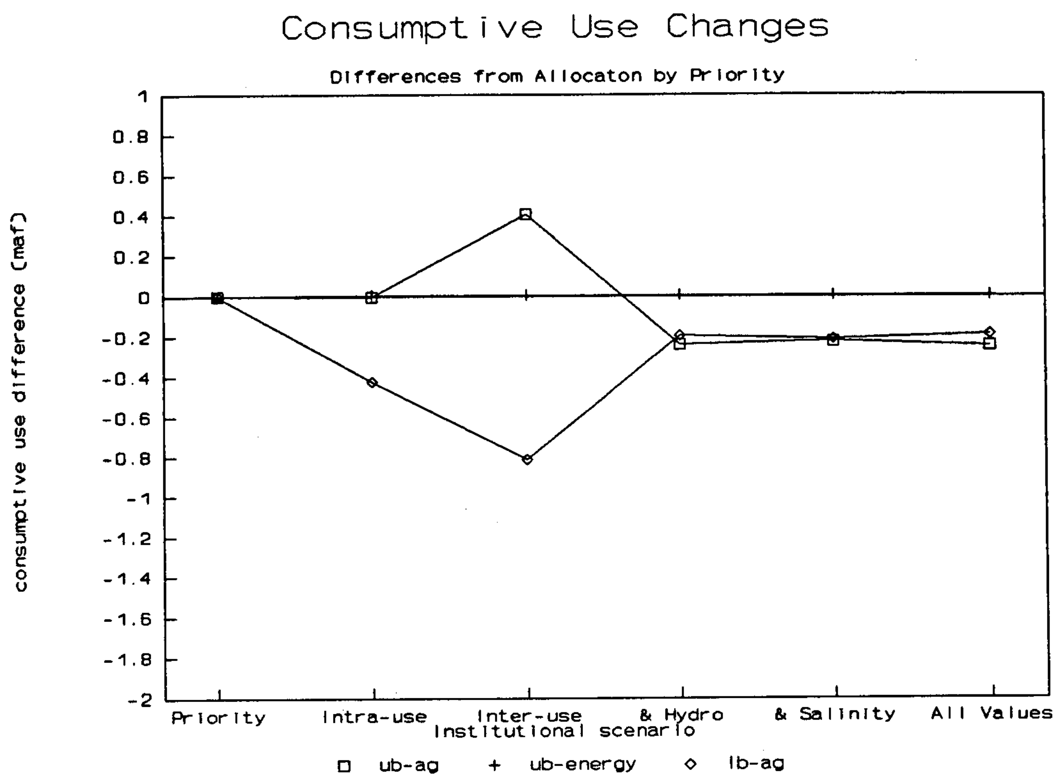


Figure 8.3. **Consumptive use and total surplus under Scenarios 1,2,4,7-9, respectively, year 2030 and historic lower decile flow.**



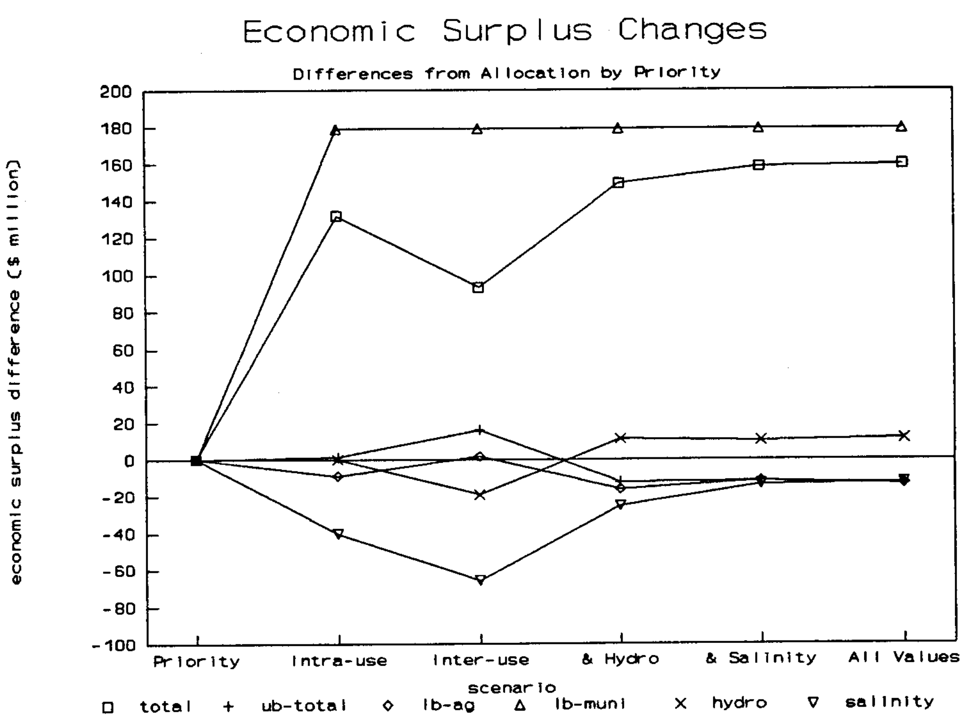


Figure 8.4. **Consumptive use and total surplus under Scenarios 1,2,4,7-9, respectively, year 1990 and synthetic lower decile flow.**

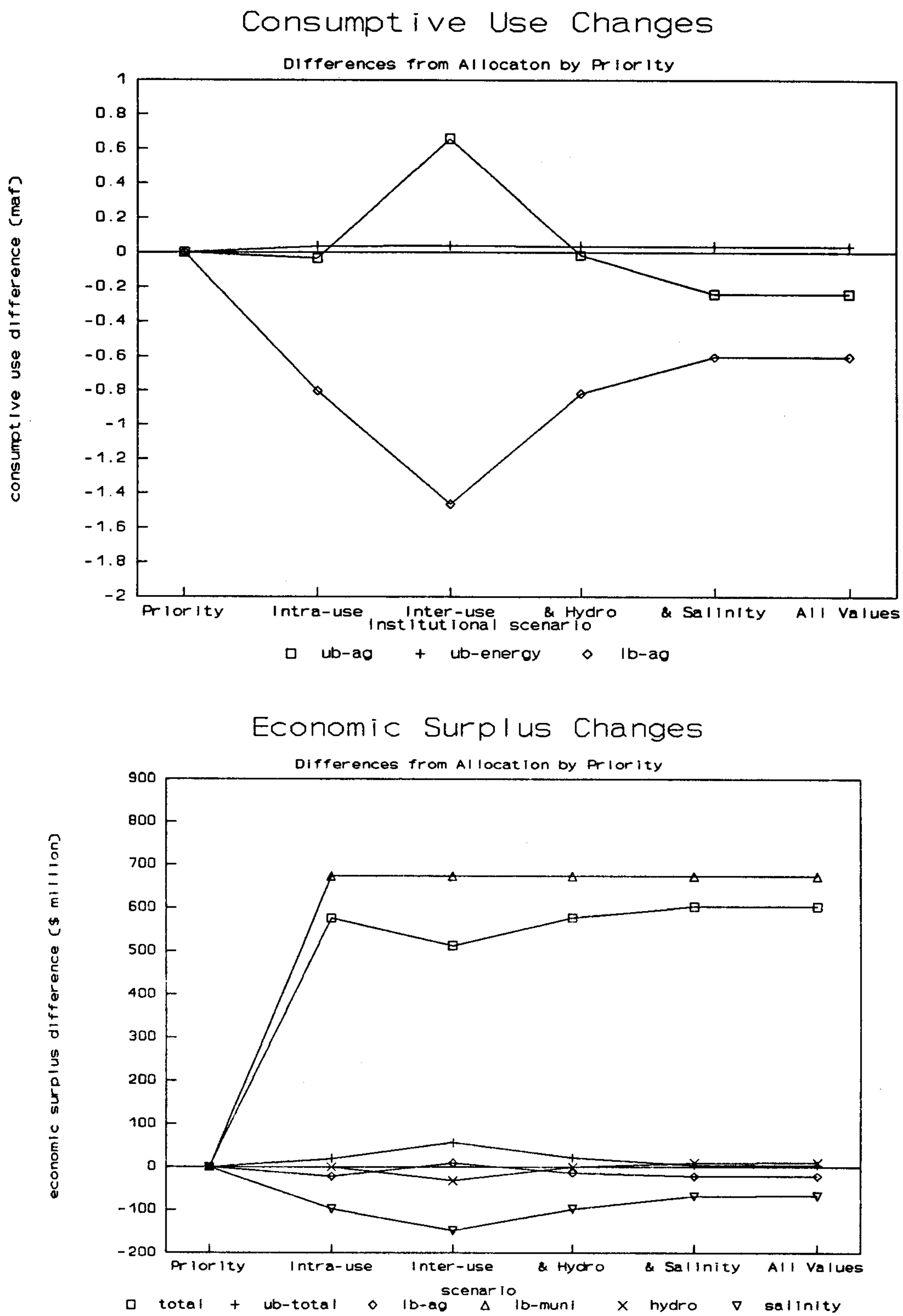
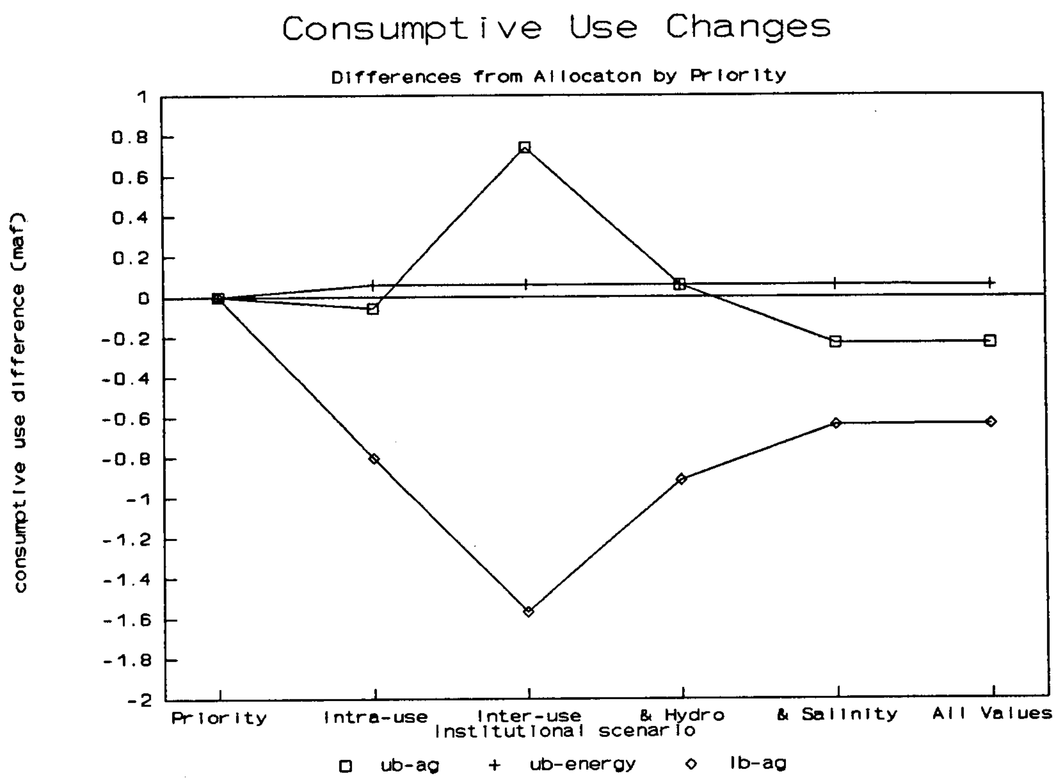


Figure 8.5. **Consumptive use and total surplus under Scenarios 1,2,4,7-9, respectively, year 2010 and synthetic lower decile flow.**



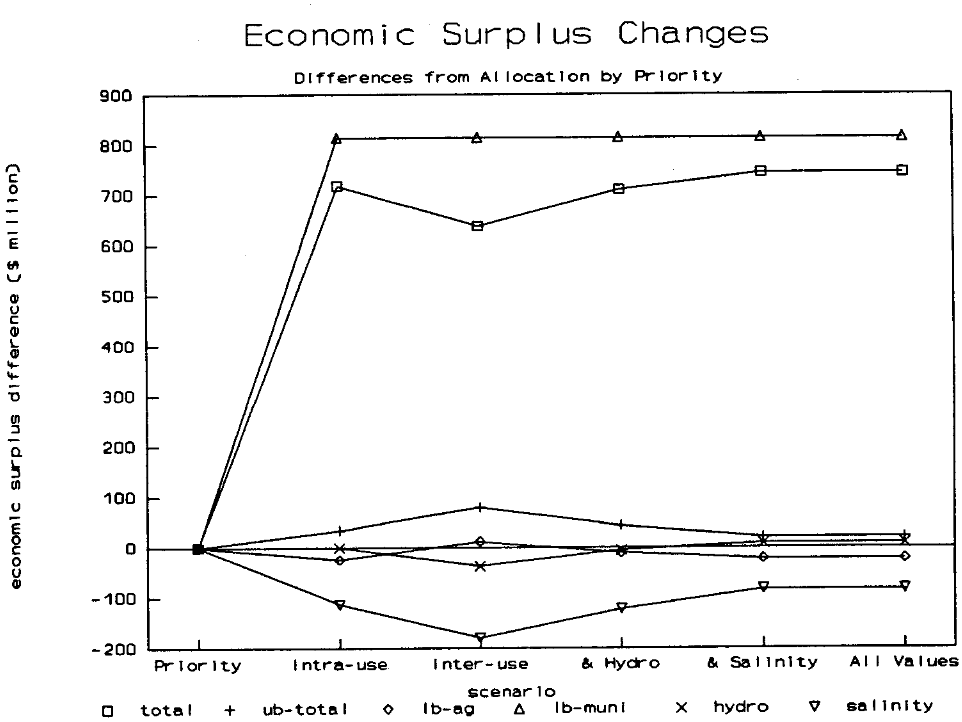


Figure 8.6. **Consumptive use and total surplus under Scenarios 1,2,4,7-9, respectively, year 2030 and synthetic lower decile flow.**

driven from $30/af (2010, "dry") to $77/af (2030, "drought") by the introduction of intrastate water transfers. Lower basin marginal values under the same institutional scenario never exceed $30/af.

Group 2: Interstate Transfers for Consumptive Uses

The high upper basin marginal values with severe shortfalls under "drought" conditions indicates that water transfers based on consumptive use values may not always move water from upper to lower basin uses. Surprisingly, in all except the base model definition, water transfers resulting from maximizing only consumptive use benefits are from the lower to the upper basin.

The interpretation of this result is straightforward. Water values for production of low value crops, particularly alfalfa hay, are similar in the upper and lower basin. Under the Compact, upper basin producers would suffer significant water shortfalls during "drought" while lower basin producers would enjoy full water deliveries. Marginal water values in the two producing regions under such conditions are significantly different and gains from trade would be possible. A contributing factor to this result is the somewhat strict limitation placed on acreage reductions in upper basin agriculture in the Grand Valley linear programming model. This causes more inelastic demand than would result with constraints allowing larger acreage reductions. While such limitations are believed realistic in the Grand Valley where average farm size is small and farming is not the primary income source for many operators, this may not hold throughout the upper basin.

While consumptive use values are increased by allowing interstate transfers, such transfers in most cases actually decrease net benefits from use of Colorado River water. Where significant transfers from lower basin to upper basin are shown in model solutions, hydropower and salinity dilution benefits are significantly decreased. In the most extreme case, year 2030 demand and request levels with "drought" flow levels, interstate transfers based on consumptive use values alone (Scenario 4) result in increased benefits in consumptive uses of $24 million, but the losses in hydropower production and from increased salinity damages are $105 million.

Group 3: Scenarios Incorporating Nonconsumptive Use Values

If the value of Colorado River water in all uses is considered, large water transfers from upper to lower basin are predicted under all model definitions. The actual levels given in the model solutions must be considered highly tentative, as they are based both on artificial constraints on the level of such transfers and extensions of upper basin demand functions beyond their valid range. Imposing limits on transfers is considered the most unrealistic factor; for low water quantities the analytic form of the upper basin demand functions is probably an upper bound on actual water demands. In related work by Lee (1989), estimated transfers from salt loading upper basin agricultural sectors based on lower basin municipal damages and agricultural use benefits and salinity damages exceed 85 percent of present use. In the research presented here, the marginal value of upper basin water for consumptive uses, hydropower, and salinity dilution (Scenario 9) ranges from $96/af under 1990 "dry" conditions, to $141/af with year 2030 "drought" conditions.

Sensitivity of Model Results

The results presented above are dependent on the specification of water supply and demand functions used in each individual model definition. The estimated water allocations and net benefits given in Tables 8.7 - 8.11 and Figures 8.2 - 8.6 are examined below for sensitivity to alternative demand levels in major sectors. Allocation under normal flow levels with anticipated future demand and request levels is also discussed.

Southern California Municipal Demand for Colorado River Water

The role of alternative supply sources in meeting future water demand in southern California urban areas is not considered in detail in this research. It is clear, however, that availability and cost of alternative supplies introduces significant uncertainty in valuing the level of benefits from transfers of Colorado River water. In all model definitions, alternative supplies are assumed constant over time. Additional water resources are available within California, both in existing agricultural uses and from potential development of new supplies in far northern California. The cost of delivering 1 maf from new supplies using excess capacity in State Water Project aqueducts is given as $400/af (1989 dollars) by Vaux and Howitt (1984). Existing agricultural uses in southern California utilizing within state supplies have marginal values of $45/af and could be delivered for an additional $100/af (Vaux and Howitt).

If water supplied from these alternative sources grows at the rate of population growth in the MWD service area, then the marginal values for raw Colorado River water are reduced to $200, $370, and $460/af for years 1990, 2010, and 2030, respectively. The consumer surplus gains (exclusive of salinity damages) from increased deliveries of Colorado River water range from $75 million (1990, historic lower decile flows, giving a 260 kaf/year shortfall) to $500 million (2030, 800 kaf/year shortfall) annually. These figures should be compared to surplus gains of $100 and $800 million calculated with fixed alternative supplies.

If the low price elasticity (-0.15) of municipal water demand at average consumption and price used in CRIM is replaced by the elasticity of -0.40 used by Vaux and Howitt, then consumer surplus gains from water transfers calculated above would be further reduced. If alternative supplies increase with population and the high elasticity is used, the marginal value of raw Colorado River water ranges from $170/af in 1990 to $260/af in 2030. The consumer surplus gains from the shortfalls given above are $50 million in 1990 and $260 million in 2030.

The range of estimated benefits to southern California municipal water users results from differing assumptions on alternative supply sources and elasticity of municipal water demand. Under all assumptions, water transfers to Colorado River Aqueduct capacity limits are indicated by model solutions; the lowest marginal value estimates are only somewhat greater than 1990 salinity damages of $130/af calculated in Chapter 6, however. The changes in allocation discussed in this chapter are thus unaffected under most assumptions on southern California municipal water supply and demand.

Flow Levels

The level of water shortfalls to the Colorado River Aqueduct and other consumptive users is dependent on particular model definitions of water flows and demands. The two flow levels presented in the analysis both simulate dry conditions; during wetter periods with higher river flows lower basin shortfalls are unlikely given existing demands. Under the base model definition the lower basin shortfall is estimated to be 260 kaf/year; this estimated shortfall is a very small proportion of, and smaller than the measurement error for annual Colorado River basin flows and consumptive uses. Consumptive use benefits of water transfers with the base model definition given above best represent benefits under a small supply shortfall, rather than at a well-defined annual flow level. Any slight flow increase over that used with the base model definition clearly results in full satisfaction of existing requests; benefits to consumptive users from water transfers are thus eliminated.

Nonconsumptive use values are relatively insensitive to flow levels, however. This is clearly shown by the narrow range of marginal water and salt load values across model definitions with the institutional scenario allowing water transfers for all purposes (Scenario 9).

Agricultural Consumptive Use Values

In all models, allowing intrastate trade results in transfers from agriculture to municipal use (lower basin) and fossil fuel based energy production (upper basin) up to maximum allowed levels based on requests by existing (and anticipated future) users. Because of the enormous difference in marginal values, this general result is insensitive to a very large range of plausible agricultural, municipal, and industrial water use values.

The economic value of water in production of hay and feed grains is generally believed small relative to its value in other uses, but the precise value is difficult to deduce. The need to impute returns to management and land, in addition to the large magnitude of revenues and costs relative to profits makes valuation difficult. It is estimated that the uncertainty in valuing Grand Valley and Imperial Valley water is at least $10/af at the margin. The results presented above use marginal values of $9/af and $18/af for upper and lower basin (consumptive) water use, respectively, at maximum delivery levels. If demand for animal feed from lower basin producers is very inelastic as suggested by Konyar and Knapp (1990), then large water transfers would in fact be much more costly (in a social sense) than anticipated in the analysis presented here. In addition, marginal water values give a lower bound on the opportunity cost of water transfers from agriculture; if transfers occur across all uses, then actual costs are determined by (higher) inframarginal water values.

Extension of the demand functions for these areas to others in the basin introduces considerable additional uncertainty. Significant pumping of irrigation water is or will be required in several upper basin locations; the cost of large pumping lifts is large relative to marginal water values, but is difficult to estimate precisely given unstable energy prices. Viable farm sizes and technologies may also be affected by energy prices (Hamilton and Whittlesey, 1986). The Imperial Valley may be the most productive of the lower basin agricultural sectors, leading to overvaluation of other lower basin agricultural water uses.[23]

It is not possible here to conclude with confidence whether the marginal consumptive use is located in the upper or lower basin. This holds both at full delivery levels and under proportional consumptive use reductions in the basins. Because the magnitude and direction of interstate transfers when only consumptive uses are considered is determined by marginal values in upper and lower basin agriculture, the level of transfers must be interpreted with extreme caution. Since the difference in value between upper and lower basin agricultural use is small however, it can be concluded with confidence that net benefits from consumptive uses generated through interstate transfers would be small.

Hydropower Production and Salinity Dilution Values

While the direction of water transfers with institutional scenarios allowing simple interstate trade is ambiguous, the incorporation of nonconsumptive use values gives the clear result that reductions in marginally valued upper basin uses generates significant net benefits. Upper basin water for hydropower production is conservatively valued at $46/af, based on social opportunity costs of 35 mills/kwh for alternative base load production.[24] Inclusion of peaking power values would substantially increase the value of avoided costs in utilizing hydropower production.

The value of upper basin water for salinity dilution is about $50/af given present demand levels, river salinity levels, and assumptions on salinity damages in agricultural and municipal uses. Most salinity damages are believed to occur in municipal uses, but their measurement is difficult as discussed above in Chapter 5. Estimation of agricultural damages is also subject to considerable uncertainty. Choice of appropriate lag times, and thus discount factors, for changes in upper basin water use or salinity loading to be reflected in reduced lower basin damages is also uncertain. It is difficult to give a quantitative estimate, but it is possible that salinity dilution values could be a factor of two greater or less than those presented here.

The discussion on hydropower and salinity dilution values strongly suggests that the opportunity cost of upper basin water for all lower basin uses substantially exceeds its marginal value in upper basin agricultural production. The economically efficient level of transfers is less well determined however, due to the difficulty in valuing very large reductions in upper basin water. This research suggests that the level is a significant proportion of existing upper basin agricultural use, particularly given the assumption of no salinity loading outside the Grand Valley. The actual levels presented in the model results are, however, dependent on the artificial restriction limiting transfers to the smallest of 33 percent or 15 percent of allocations under the Compact priorities.

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[23] All Imperial Valley diversions are consumptively used, however. Marginal consumptive use values are probably higher in other lower basin agricultural regions because return flows can be utilized by downstream users.

[24] One study of proposed additions to the Hoover Dam power plant for increasing peaking power capacity values the additional power at 154 mills/kwh in 1982 dollars (USBR, 1982). While this figure is exceptionally high, the value of peaking power is generally about double the value of base load production.

Limitations of the Model Specification

The model used in this research includes economic demand by most of the major users of Colorado River water. There are notable exceptions. While deliveries to the Central Arizona Project are determined under present institutional priorities, the value of Project uses is not considered. Within each model deliveries are fixed by priority, but opportunities for gains from transfers with other sectors are not considered.

Upper basin municipal uses are treated in much the same way. Reductions in upper basin municipal use, proportionate to those suffered by other upper basin users, are made when the Compact requirement at Lee's Ferry is constraining. Gains from subsequent transfers are not considered.

The actual distribution of water rights held by different upper basin sectors is not included in the analysis, nor are individual state allocations in assigning upper basin shortfalls. While the model provides little insight to local water users as a result, basinwide patterns of use are clearly shown.

CHAPTER 9
CONCLUSIONS AND POLICY IMPLICATIONS

Empirical policy analysis should supply information and insights relevant and useful in policy decisions. The implications of this research for policies affecting allocation of Colorado River water are discussed below, including several cautions. The role and prospects for achieving allocative efficiency improvements through institutional change are first discussed; significant limitations of both existing institutions and potential market mechanisms are identified. Those sectors most likely to be significantly affected by institutional change are then identified. The distribution of impacts among players under different levels of institutional change is then examined, including estimation of the social costs of maintaining regional equity in allocation of basin water resources. A final comment on interstate markets for Colorado River water is then made.

This research has identified patterns of water allocation which clearly increase beneficial use Colorado River water resources. Economic efficiency gains, measured by net increases in economic surplus from consumptive and nonconsumptive users of basin water, are possible under most conditions by reducing upper basin agricultural uses. However, the generality of this conclusion holds only if economic values of instream water for hydropower production, of upper basin water for salinity dilution, or of both uses, are included. If only consumptive uses are considered, and modest within-state water transfers are permitted, large economic gains from interbasin water reallocation are unlikely.

Economic efficiency improvements are shown using estimates of present and future economic demand, and under two levels of basin water flow. The first flow level is equivalent to estimates of the long-term mean, but is well below mean flow levels for this century. The second flow level, representing drought under long-term flow estimates, or a climate change induced reduction in mean flows, is used to simulate the performance of alternative water allocation institutions under stress.

The magnitude of economic efficiency gains is strongly dependent on transfers of agricultural water at their marginal values; where inframarginal agricultural water values are most appropriate, efficiency gains of water transfers from agricultural to municipal uses are significantly reduced.

Institutional Change and Allocative Efficiency

Markets, Planning, and Models

If a commodity value is known across all users for all levels of use, and transportation costs are known, then economically efficient allocation is simulated by the allocation which maximizes the total value of the commodity, summed over all users. This research identifies economic surplus maximizing allocations of Colorado River water under a number of assumptions about the relevant users and values.

The modeling effort by itself provides little insight into institutions for achieving such allocations, however. For example, the efficiency maximizing allocations estimated by CRIM could in principle simply be dictated (with appropriate compensation) by a central planner. Alternatively, free market transfers among owners and potential owners of the commodity, would, under idealized conditions lead to the same allocatively efficient allocation.

It is assumed for purposes of the following discussion that movement towards the allocatively efficient solutions presented in the previous chapter is desirable. Within this context, realistic water allocation institutions for achieving such outcomes are considered. The potential for existing institutions to increase allocative efficiency in water use will be discussed, in addition to prospects for an increased reliance on water markets. The role of potential water markets is approached by considering the estimated benefits from participation by different water users.

Within-State Water Allocation

Water allocation within state boundaries in the Western U.S. has traditionally been controlled by state law based on the prior appropriation doctrine. The date at which water was first put to use establishes both the size of the right and its relative priority. Perfected rights are entitlements to the use of water, and, like other property rights are unlikely to be arbitrarily altered for promotion of economic efficiency or other goals, even with payment of compensation. Thus an administered solution to achieving allocative efficiency in water use within state boundaries is not a significant possibility.

Transfers based on market incentives offer the most likely vehicle for achieving allocative efficiency in state water allocation. While subject to regulation when changes in point of diversion and purpose of use are involved, market transfers are generally permitted and do occur under state water laws (MacDonnell, 1990, Saliba and Bush, 1987). The strict requirements faced by many potential transfers are a critical factor in limiting the present scale of intrastate water transfers (in addition to physical limitations on water transportation and storage.) Legal rights to water made available through improvements to delivery and irrigation systems (salvaged water) are generally either nonexistent or unclear under the "beneficial use" test which must be met by water users. With uncertain property rights, transactions such as that between MWD and the Imperial Irrigation District have proven to be difficult to achieve. Relatively small changes to existing state water allocation institutions could lead to the establishment of more complete intrastate water markets, promoting increased efficiency in use of Colorado River water. Because the majority of net benefits from reallocation of basin water can be achieved through transfers within California, the importance of state water markets for promoting efficient use of basin water should be emphasized.

Interstate Water Allocation in the Colorado River Basin

Institutions controlling interstate allocation of Colorado River water are based on a history of negotiation and compromise between basin states. It is unlikely that wholesale changes to the distribution of state water rights established by the Colorado River Compact, the U.S. Mexican Water Treaty, and Arizona v. California will be made through either legislative or judicial action. Clarifying the nature and place of Indian rights within the existing basin water allocation institutions could, however, induce significant changes in the conditions of some non-Indian water rights. Such changes would not be made on the basis of economically efficient allocations, however, but on historic rights of Indian reservations to water for use on "practicably irrigable lands" under the Winters doctrine of reserved water rights. There is some chance that Indian water rights established under the doctrine could become marketable, perhaps opening a seminal market not bounded by Compact restrictions. This would apparently promote the achievement of efficient allocation, but could actually decrease allocative efficiency under certain conditions. This counterintuitive result could occur because nonconsumptive use values are unlikely to be included in hypothetical market transfers for consumptive uses.[25]

Water Allocation and Nonconsumptive Uses

The institutions discussed to this point include only those charged with allocating entitlements to consumptive uses of basin water. Other values may be equally significant from a national accounting stance. Water values for hydropower production and salinity dilution appear to be substantially greater than in marginal upper basin consumptive uses, though the valuation of salinity damages remains highly uncertain. The Salinity Control Act of 1974 established an upper bound target for salinity concentrations measured at Imperial Dam, and has authorized numerous salinity control projects throughout the basin to help meet this goal. While these projects viewed alone may show benefit-cost ratios greater than unity, particularly in regions producing heavy salinity loading such as the Grand Valley, they do not generally consider downstream consumptive use or hydropower values. Further, dilution benefits from changes in consumptive use levels are not generally considered.

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[25] This is a classic illustration showing that establishment of first best pricing in a second best environment can actually reduce economic efficiency. In this case the presence of physical externalities establishes the second best environment.

Basin reservoirs are managed to maintain at least the minimum storage required for hydropower production, and to meet certain electric power peaking demands. There are no institutions which compel or encourage upper basin users to consider the opportunity costs of upper basin consumptive uses in terms of lost power production.

Public Goods and Colorado River Water Resources

The benefits of reduced upper basin consumptive use have public good attributes. Marginal impacts from upper basin water use are registered on lower basin agricultural users (including salinity impacts), salinity induced damages to southern California municipal users, and in hydropower generation.

Institutions designed for efficient allocation of private goods cannot lead to optimal allocation of upper basin water: in additional to rival users, there are significant downstream nonrival users. A government or administrative role in representing nonrival users is necessary for achieving allocative efficiency when nonrival users are unable to act as a group. This almost certainly applies to lower basin nonconsumptive users of Colorado River water. A possible place for such representation to occur would be in conjunction with salinity control efforts. If programs presently targeting reductions in salinity loading also considered basinwide benefits of consumptive use reductions, efficiency gains would likely result.

Interstate water markets based on consumptive uses alone would be difficult to establish; incorporation of the additional nonconsumptive use values into a more general market is even less likely. Efficient markets require that resources be rival and excludable, and that use values are well known. Because Colorado River water does not satisfy these criteria, a hypothetical interstate consumptive use market would not achieve allocative efficiency.

Colorado River Users under Existing Institutions

Consumptive Users

Southern California municipal water users and upper basin junior water rights holders are vulnerable to significant shortfalls in the event of extended, but not unexpectedly dry conditions in the basin. The exposure of these two very different groups to possible supply reductions induced by low Colorado River flows is, respectively, new and anticipated. This study suggests that without diversions for the Central Arizona Project, a basin water shortfall would still be quite unlikely. Indeed, given present upper basin request levels, use for upper basin consumptive purposes is unlikely to be constrained by the Lee's Ferry delivery requirement of 8.25 maf per year. Significant development above present levels, however, would inevitably lead to a greater likelihood of shortfalls in dry periods. Other basin water users are well protected during dry periods, and might not experience any of the opportunity costs of water shortages experienced by more junior users.

Nonconsumptive Users

A second category of water users experiences costs on a continual basis because of salinity levels in Colorado River water. The costs, which cannot be directly observed, presumably change continuously as salinity concentrations in river water fluctuate. This category includes lower basin irrigators, particularly in the Imperial Valley, and, again, southern California municipal water users. Salinity concentrations are determined by water flows into the system, salinity loading from natural sources and (mostly upper) basin water users, concentration of salts through consumptive uses, and exports of water and salinity. Opportunity costs are almost certainly not internalized by the relevant water users.

Electric power consumers throughout the West benefit from basin water use. One very significant electricity consumer is again the southern California municipal water user who indirectly consumes 2,000 kwh per delivered acre-foot of water. The importance of this particular consumption is that over 60 percent is derived from hydropower generation within the basin (MWD, 1988); electric consumption by MWD alone represents about 15 percent of total basin hydropower production.

Other Users

Many players have been excluded from this research. The economic value of large consumptive uses served by transbasin diversions to the Colorado Front Range and users of Central Arizona Project water are not considered. Salinity damages to Central Arizona Project users are not valued. The economic value of many small consumptive uses in upper and lower basins is similarly omitted.

This work has by necessity excluded from formal analysis many others with economic interests in nonconsumptive uses in Colorado River resources. Basin reservoirs are an important recreational resource for many thousands of people. Free flowing portions of the river and its tributaries are highly valued by others, while maintenance and recovery of the ecological integrity of basin rivers is a significant goal for many people throughout the United States.

Winners and Losers under Institutional Change

All players included in this study could be affected by institutional change in basin water allocation. If only state markets developed, then the major impacts would be felt in California. In an interstate market in Colorado River water, there would be impacts to all users.

Impacts of Intrastate Water Transfers

Removing barriers to water marketing within California would likely result, over the forty year planning period studied here, in significant transfers between southern California municipal users and California agricultural water rights holders. Any reallocation which either elevated MWD's junior rights, or reduced existing consumptive uses by more senior rights holders would be a gain for southern California municipal users. Model results indicate that with present demand these municipal users would benefit in dry periods from water transfers up to the Colorado River Aqueduct capacity if marginal costs (i.e. foregone benefits in alternative uses) are less than $300/af. Imperial Valley irrigators could benefit from such a transaction at prices as low as $20/af. For comparison, in their regional trade model covering water demand throughout California, Vaux and Howitt (1984) found marginal values of $210/af in southern California municipal uses and $45/af in Imperial Valley agriculture in a 1980 scenario (values adjusted to 1989 constant dollars using the GNP deflator). For 1995 they estimated values of $360/af and $60/af, respectively. Their study showed very large transfers from the Imperial Valley (over 1 maf) in both scenarios, accounting for much of the difference in marginal values.

The total value to southern California municipal users of eliminating the 260 kaf shortfall found under existing priorities with the base model definition is estimated at $100 million annually. If distributed over the estimated MWD service area population of 15 million in 1990, annual benefits (not including costs paid to Imperial Valley irrigators, or salinity damages) are about $7 per capita. Estimated annual benefits rise to $800 million in year 2030 for eliminating a 800 kaf/year shortfall, given a projected population increase to 23 million. Per capita total benefits are then $35 annually. If acquisition costs are $130/af (the cost to MWD in the recent transfer agreement with the Imperial Irrigation District, or IID), then the net benefit (still excluding salinity damages) to southern California municipal water users is $30 per capita per year.

Both southern California municipal users and owners of IID shares are likely to be significant winners in any water transfers. The difficulty of negotiations leading to final agreement between MWD and IID (1988) on transfer of 100 kaf may have been the result of uncertain property rights in transfer of the salvaged water. It is difficult to identify any losers in this particular transfer agreement. If a transfer impacted crop production, then both laborers employed in the crop production and crop consumers would be losers.

Impacts on salinity levels and hydropower generation from transfers between California users of Colorado River water would be small. The dominant salinity impact would be increased damages to southern California municipal water users from higher salinity levels. In principle this impact would be included in decisions by MWD on importing Colorado River water. It is not clear whether this would actually occur, however, given the internal goals of MWD.

Impacts of Interstate Water Transfers

Next considered are impacts of potential interstate water markets based on consumptive use values. Model results suggest the possibility of upper basin to lower basin transfers and vice versa under different conditions. Though suggested by the future model scenarios, upper basin right holders are unlikely to look to lower basin agricultural users as potential sellers of water. The difference in consumptive use values, even with large shortfalls in upper basin agriculture during severe drought would be unlikely to cover the transactions costs of interbasin transfers. More likely, reallocation from lower to upper basin would be attempted at the political level through direct amendment of the Lee's Ferry delivery obligation, perhaps to the detriment of Mexican users.

Proposals for interstate water markets appear much more likely to originate from southern California municipal water users than from upper basin users.[26] It is suggested by this work that marginal water values in lower basin agriculture are unlikely to significantly exceed those in upper basin agriculture (relative to estimated differences in marginal values in municipal and agricultural uses), and that transactions costs of transfers within California are likely to continue to be lower than those for interstate transfers in the basin.

If market transfers of upper basin water to lower basin municipal use do occur, they would most likely be motivated by a complete exclusion of lower basin agricultural water from market transactions. If California agricultural users of Colorado River water were excluded from an interstate market for basin water, then southern California municipal water users and upper basin water rights holders would be winners in upper basin to lower basin transfers. Because such transfers would significantly lower upper basin crop production there would be many upper basin losers. These indirect losses would likely be offset by indirect gains in southern California municipal areas. Reinvestment of transfer proceeds by upper basin sellers could potentially offset a significant portion of indirect losses in the upper basin. Because of the many beneficiaries and poorly understood benefits from salinity dilution, nonconsumptive use values are not likely to be considered in any market transfers.

While MWD could potentially include nonconsumptive use values in its market decisions, the marginal benefit to MWD of reduced upper basin consumptive use is only $5/af when valued at 30 mills/kwh, the cost of alternative electrical supplies available to MWD (Schempp, 1990). Also, salinity levels do not seem to be of great internal concern to MWD as an organization. Agricultural users would benefit from MWD purchases of upper basin irrigation water through reduced salinity levels, however, and would be clear winners if transfers increased flows to the lower basin.

Equity

Promotion of regional equity has long been viewed as an important social goal in the development and use of basin water resources (National Academy of Sciences, 1968). Present institutional allocation of Colorado River water is likely seen as more equitable than the alternative institutions suggested above on the basis of allocative efficiency. Any water transfers from upper to lower basin uses would move a valuable resource from a less developed to a more developed economic region. The costs of maintaining equity are estimated by the opportunity costs of upper basin water when all values for downstream users are included.

At present development levels and under dry conditions (the base model definition) the marginal value of upper basin water to downstream users is $110/af. The same water is worth about $10/af to upper basin irrigators at the margin. The difference of $100/af, or ten times the upper basin marginal value, is the annual social cost of maintaining existing Colorado River basin allocations under dry conditions. With anticipated future development, impacts of dry periods on the upper basin would be much greater. Under these conditions upper basin water is worth up to $50/af at the margin for upper basin irrigation, and its social value in downstream nonconsumptive uses is $135/af. The social cost of maintaining the existing prohibition on

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[26] Lower basin purchasers of upper basin rights could be protected from encroachment by upper basin junior rights only with revision of the Lee's Ferry delivery requirement. In the absence of such a change, however, there is little motivation under any conditions for lower basin purchases of upper basin rights.

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interstate transfers, but allowing state markets is then $85/af, or less than twice the marginal value of upper basin water. Differences in relative price levels between the southern California municipal areas and the rural upper basin could further reduce this figure. If salinity damages are presently overestimated, then the cost of excluding interstate transfers would be even lower.

Concluding Remarks

While market based interstate transfers are possible, this research suggests that they are unlikely. Potential benefits from interstate consumptive use markets which include possibilities for within state transfers are relatively small. If interstate transfers were allowed in a basin-wide water market (with no transactions costs) lower to upper basin transfers would be possible under certain conditions, in addition to the typically envisaged transfers from upper to lower basins.

Lower to upper basin transfers would be economically inefficient, however, and would result in a reduction in net benefits from use of basin water resources. If interstate transfers were to occur, they would likely be the result of constraints on lower basin within-state transfers, particularly in California. Ironically, if all water use values across all basin water users are considered, interstate transfers resulting from constraints on water transfers within lower basin states would be economically efficient.

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