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Economic values for conjunctive use and water banking in southern California

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[1] The potential and limitations of conjunctive use of surface and groundwater are explored for southern California's water supply system. An economic-engineering network flow optimization model, CALVIN, is used to analyze the economic and reliability benefits from different conjunctive use alternatives. Flexible management of additional conjunctive use facilities and groundwater storage capacity under flexible water allocation can generate substantial economic benefits to the region. Conjunctive use adds operational flexibility to take better advantage of water market transfers, and transfers provide the allocation flexibility to take better advantage of conjunctive use. The value of conjunctive use programs along the Colorado River Aqueduct, in Coachella Valley, and north of the Tehachapi Mountains under economically optimized operation of the system is examined. Results reveal reductions of economic demand for increased imports into southern California, suggest changes in the system operations, and indicate significant economic benefits from expanding some conveyance and storage facilities. *INDEX TERMS:* 1899 Hydrology: General or miscellaneous; 1857 Hydrology: Reservoirs (surface); 6344 Policy Sciences: System operation and management; 1884 Hydrology: Water supply; 1812 Hydrology: Drought; *KEYWORDS:* conjunctive use, California, optimization, water management, economic optimization, water transfer

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1. Introduction

[2] Southern California's water system (south of the Tehachapi Mountains) imports up to 70% of its 12.3 km^3 (10 million acre-feet, or maf) annual water use. In addition to relying on imported water, southern California employs extensive groundwater supplies, 1.5 km^3/yr, and a limited amount of local runoff [*California Department of Water Resources* (*CDWR*), 1998]. The main urban demands are located in the western part of the region, and major agricultural areas in the east. Covering only about 7% of California's land area, the South Coast houses about 54% of California's population (18 million people) [*CDWR*, 1998]. Sources of imported water include the State Water Project (SWP), the Los Angeles Aqueduct (LAA), and the Colorado River (CR). Voluntary transfers are important for allocating water among users inside the region [*Johns*, 2003].

[3] California's population and urban water demands are expected to increase significantly in coming decades, growing from 32 million people in 1995 to 47.5 million in 2020 [*CDWR*, 1998]. About 7 million of this growth is expected for southern California. Urban water demand, despite water conservation and recycling efforts, continues to grow. Average statewide urban use was 10.8 km^3 in 1995, with a growth to 14.8 km^3 forecasted by 2020 [*CDWR*, 1998]. On the supply side, traditional imports from the Colorado River and the Owens and Mono Basins are being curtailed. The Colorado River Board's 4.4 Plan would reduce California's annual diversion of Colorado River water to 5.4 km^3 (4.4 maf), a reduction of about 1 km^3/yr. Meanwhile, court decisions providing additional environment flows to Mono Lake and Owens Lake have substantially reduced LAA deliveries. SWP supplies also are uncertain, depending on the results of various regulatory and planning processes. Predictions for growing demand for water and unpredictable and diminishing supply have led water managers to look at water less traditional options. These include water transfers and markets, water conservation, wastewater reclamation and reuse, seawater desalting, water banking, and conjunctive use.

[4] This paper examines the effects of water markets and flexible conjunctive use operation with potential additional facilities in southern California. The model results offer insights into the economic benefits of more efficient operation of the system, both for the region and different users [*Pulido-Velazquez*, 2003]. User's marginal willingness to pay and trans-boundary economic values are examined, and estimates are made of the economic value and usefulness of various proposed conjunctive use programs. Since flexible conjunctive use operations imply a substantial change in

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system management, some general operational implications also are presented.

2. Conjunctive Use in Southern California: Promising Alternatives

[5] Conjunctive use is a strategic element of California's water management challenge. The Association of Groundwater Agencies of California (AGWA) estimates that over 26.5 km^3 of additional groundwater storage is available in southern California groundwater basins, assuming resolution of institutional, water quality and other issues. Existing conjunctive use programs in southern California provide an estimated 3.1 km^3 of water per year [*AGWA*, 2000]. Conjunctive use programs include both dry-year (longer-term storage) and short-term seasonal programs, storing "surplus" surface water underground to improve deliveries during dry seasons and droughts. Metropolitan Water District of Southern California (MWDSC), the main urban water wholesaler in the region, is conducting technical studies and negotiating agreements with local agencies to increase deliveries and reliability of water supplies through conjunctive use programs using aquifers in its service area, along the Colorado River Aqueduct (CRA) and the California Aqueduct [*MWDSC*, 2000, 2002]. Cadiz, Upper Chuckwalla, and Hayfield are the most important programs for conjunctive use along the CRA. Under these programs, MWDSC could store CRA water underground when it was available, pumping stored water in dry periods. MWDSC also could store CRA water by recharging the Upper Coachella Valley aquifer. The feasibility of developing conjunctive use storage in the Lower Coachella Valley, currently in overdraft, is also under study [*Coachella Valley Water District* (*CVWD*), 2002]. Important conjunctive use programs to store SWP water are occurring in Kern-Delta, Semitropic, and Arvin-Edison, in the Tulare Basin. MWDSC can store water in these groundwater basins, either through direct spreading or in-lieu deliveries to local farmers. A program also exists to store unused Colorado River water in Central Arizona aquifers [*MWDSC*, 2002], offering possibilities for interstate banking.

3. Modeling Approach

[6] CALVIN (California Value Integrated Network Model) is a network-flow based economic-engineering optimization model of California's major water supply system [*Jenkins et al.*, 2001; *Draper et al.*, 2003]. The model explicitly integrates the operation of water facilities, resources and demands for California's inter-tied water system, to suggest economically desirable water operations and allocations. Agricultural and urban demands are represented by economic value functions for a year 2020 level of development, based on the California Department of Water Resources Bulletin 160–98 population and land use estimates [*CDWR*, 1998]. Monthly operation and allocation decisions are made based on the optimization of the system's performance over a 72-year period, using 1922–1993 monthly historic time series of inflows (which represent a broad range of likely hydrologic conditions), and are limited by environmental flow requirements and facility capacities. CALVIN uses HEC-PRM, Hydrologic Engineering Center-Prescriptive Reservoir Model [*U.S. Army Corps of Engineers*, 1994], a generalized network flow optimization solver with gains and losses. The solver minimizes the cost of all flows in the network, with costs on each link representing piecewise linear economic benefits and variable costs throughout the system.

[7] To represent the system, CALVIN requires a multitude of physical and economic input parameters. Physical parameters include infrastructure facilities, hydrology and environmental requirements. Economic parameters include penalty-demand functions and variable operating costs. Generated monthly time series of flows, storages, scarcities, scarcity costs, marginal values, and willingness-to-pay results are postprocessed, providing considerable information and insight for policy and operations planning.

[8] CALVIN achieves optimal conjunctive use operation to maximize net economic benefits of water deliveries to agricultural and water users, within limits of water availability, infrastructure, and environmental and other constraints. Facilities represented in CALVIN include surface and groundwater reservoirs, conveyance facilities (canals and pipelines), and pumping, recycling, and recharge facilities.

[9] Groundwater basins are represented as lumped reservoirs with a known capacity, and treated similarly to surface reservoirs. In some cases, recoverable conveyance losses, inter-basin flows, streamflow exchanges and deep percolation from rainfall have been preprocessed into a time series of monthly groundwater inflows. A constant unit pumping cost is assumed (fixed head), estimated for an average depth to groundwater. The highly simplified representation of the aquifers is required by the limitations imposed by the network flow solver, and by lack of data regarding the groundwater hydrology and use.

4. Southern California Model

[10] The region modeled comprises the main inter-tied water supply and demand system from the Tehachapi Mountains to the Mexican border, including SWP supplies from the north, Colorado River and Eastern Sierra supplies and major urban and agricultural demands (Figure 1).

[11] Three main model runs were developed to explore conjunctive use possibilities for southern California's water system; one is institutionally constrained and two are unconstrained, expanding and refining earlier studies [*Newlin*, 2000; *Newlin et al.*, 2002].

[12] 1. Run BC reproduces the "base case" with current facilities and operations constrained to the current water allocation policies projected for year 2020 levels of demand. SWP deliveries are allocated based on deliveries simulated in the CALSIM II Benchmark Study [*CDWR*, 2002], according to each user's contractual entitlements. The Colorado River allocation reflects the Seven Party Agreement [*Newlin et al.*, 2002]. Current LAA operation is represented as a time series of deliveries to the MWD system.

[13] 2. Run U represents the "unconstrained case," with current facilities but with, in effect, an ideal market with flexible water allocation driven only by an economic objective function, without current water rights or operating rules. Comparison of alternatives BC and U illustrates economic value of changing current institutional constraints for more flexible water exchange and conjunctive use operations, updating and refining earlier estimates [*Newlin*

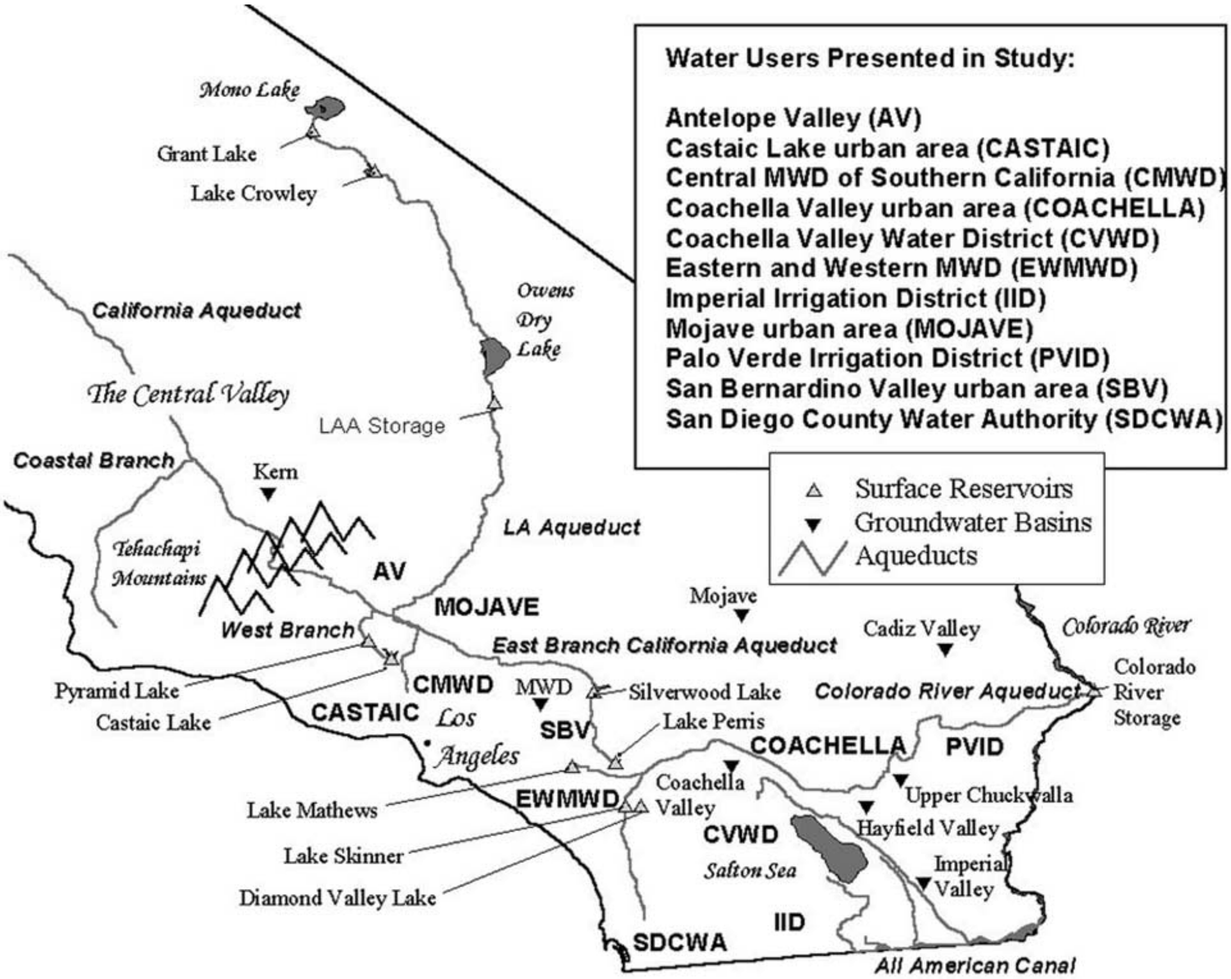

Figure 1. Southern California's water system and main users.

et al., 2002]. This run includes new conjunctive use facilities with zero capacity, allowing calculation of shadow values for these facilities.

[14] 3. Run UNF represents the "unconstrained case with new conjunctive use facilities," which is described below.

[15] Comparison of runs BC and U allows us to infer reliability and economic benefits of flexible water allocation in a perfect water market (or other economically-driven operations), considering conjunctive use. Comparison of runs U and UNF illustrates the benefits of additional conjunctive use facilities in the system, the economic value of that infrastructure, promising changes in system operation, and capacity expansion values.

[16] The base case's six groundwater storage basins are Mojave (GW-MJ), Coachella (GW-CH), Imperial (GW-IM), Metropolitan (GW-MWD), Owens (GW-OW), and Antelope (GW-AV) (Figure 1). Ending storages of the optimization period (corresponding to the 1922–1993 hydrology) are constrained to equal initial storages, preventing long-term groundwater depletion. Additional capacitated facilities in run UNF include proposed groundwater storage facilities along the Colorado River (GW-Cadiz, GW-Upper Chuckwalla, and GW-Hayfield), the aggregated groundwater storage basin north of the Tehachapi Mountains (GW-Kern), and the new facilities projected in Coachella Valley for artificial recharge in the lower valley.

[17] GW-Cadiz has a potential storage capacity of 1.2 km^3 for water imported from the Colorado River Aqueduct [*AGWA*, 2000]. Project facilities would be able to deliver 5.7 m^3/s (200 cfs) [*MWDSC*, 2002] to spreading basins and back to the CRA during dry periods. Initial storage is assumed to be 50% of total storage usable by MWD in Cadiz. A lower bound of 228 million m^3/year (mcm/yr) is imposed, the supply capability estimated by MWD for multiple-dry years [*MWDSC*, 2002]. The recharge and pumping operating costs are \$21.1/thousand m^3 (tcm) and \$43.8/tcm, respectively [*Pacific Institute*, 2001]. Although the program contemplates exploiting additional native water, this aspect is neglected here due to controversies and discrepancies in estimates of natural aquifer recharge [*Bredehoeft*, 2001; *U.S. Geological Survey*, 2001]. Here only recharged water can be drawn from the aquifer. GW-Upper Chuckwalla has an estimated storage capacity of 617 mcm, with a maximum extraction capacity of 185 mcm/yr [*MWDSC*, 2002]. GW-Hayfield can hold up to 987 mcm of additional CRA water, with pumping and recharge up to 185 mcm/year [*MWDSC*, 2002]. Pumping and recharge costs are lower than in Cadiz, due to their proximity to the CRA. MWDSC also is implementing conjunctive use storage programs north of the Tehachapi Mountains, to store "surplus" SWP water in wet yeas, recovering the stored water during droughts [*MWDSC*,

Table 1. Scarcity, Scarcity Cost, and Operating Cost

		Total Annual Average					
		Scarcity, mcm		Scarcity Cost, $ million/yr		Operating Cost, $ million/yr	
Run	Description	Average Value	Percent Change From Current Policy	Average Value	Percent Change From Current Policy	Average Value	Percent Change From Current Policy
BC	constrained base case	1,454	0	1,541	0	22	0
U	unconstrained base case	1,221	−16%	226	−85%	25	16%
UNF	unconstrained base case	1,195	−18%	127	−92%	26	17%
UNF	with new CU facilities						

2002]. The main programs include water storage in Kern Delta, Semitropic, and Arvin-Edison groundwater basins. These groundwater basins have been lumped in this study as a groundwater reservoir with a combined storage capacity of 1,048 mcm (Kern, 308 mcm; Semitropic, 432 mcm; Arvin/Edison, 308 mcm). MWD can recover stored water at a rate of 148–370 mcm/yr [*MWDSC*, 2002].

4.1. Economic Value Functions

[18] Economic value functions for urban and agricultural demands, and variable operating costs and benefits drive the results of the optimization model.

[19] Urban demands are modeled with piecewise linear economic value functions, split into residential, industrial, and commercial sectors [*Jenkins et al.*, 2001, 2003]. Economic losses from urban residential water scarcity are based on economic demands curves for urban water use. Different long-term price elasticity of demand values are considered for winter, summer, and intermediate months. Demand curves are scaled by the 2020 forecast population. Industrial water demands are represented as simple linear penalty functions of water shortages, derived from an industrial survey *California Urban Water Agencies* [1991]. Urban demands included in the southern California model, derived from aggregation of smaller water agencies, are: Mojave Water Agency (MWA), Antelope Valley (AVEK), Castaic, Coachella Valley, San Bernardino Valley, Central MWD (CMWD), Eastern and Western MWD (EWMWD), and San Diego County Water Authority (SDCWA). El Centro and Ventura County are modeled as fixed diversions, using fixed monthly time series of deliveries, due to lack of data and relatively small populations. Commercial and institutional water demands are taken from 2020 estimates and are assumed fixed, since these demands are usually more price-insensitive and no information on the cost of commercial scarcity could be found in the literature.

[20] Agricultural water demands include Imperial Irrigation District (IID), Palo Verde Irrigation District (PVID), and CVWD. Year 2020 acreages for agricultural lands availability are assumed. The economic value of water for agricultural demands is derived from the Statewide Agricultural Production model, SWAP [*Jenkins et al.*, 2001, Appendix A]. SWAP is a quadratic optimization model that simulates an agricultural area's choice of crop, planted area and investment in irrigation to maximize farm profit within water, land, technology, and capital availability constraints.

[21] Variable operating costs and benefits include fixed-head pumping cost for groundwater and surface conveyance, fixed-head hydropower benefits (for Mono Basin, Owens Valley, and locations on the SWP and the All American Canal), and costs for recharge, water treatment, wastewater recycling, urban water salinity, and local distribution [*Jenkins et al.*, 2001, Appendix G]. Fixed costs are considered sunk.

4.2. Operation Constraints

[22] Several constraints on flow and storage limit system operations. Infrastructure and environmental constraints are included. Institutional constraints vary between model runs. For each constraint, resulting shadow values (Lagrange multipliers) reflect the economic value for the region of loosening the constraint by one unit, i.e., the marginal willingness-to-pay for changing the constraint.

[23] Infrastructure constraints include maximum, minimum or fixed flows on particular links. Surface and groundwater reservoirs have maximum and minimum storage levels. Although CALVIN does not include explicit environmental value functions, environmental constraints represent minimum streamflow constraints, fixed deliveries, and minimum storages at various locations. Explicit environmental constraints in this southern California model are Mono Basin lake level and minimum in-stream flows, and a fixed diversion of 63 mcm/year to Owens Lake to mitigate dust storms [*Jenkins et al.*, 2001, Appendix F]. Institutional constraints reflect current projected water allocation and operation policies for year 2020 demands, and are applied in the base case model run.

5. Economic Value of Conjunctive Use in Southern California

[24] Table 1 shows the average annual scarcity, scarcity cost, and operating cost for the different alternatives. Water scarcity is defined as the difference between modeled deliveries and the water quantity users would take were it freely available at zero marginal cost. Flexible water allocation and conjunctive use operation in an ideal water market significantly reduce scarcity and scarcity cost (16% and 85% reduction respectively from alternative BC to alternative U). More water is allocated to urban demands, with higher marginal economic value and greater reuse possibilities, since more urban return flows can be recycled. The flexibility of optimized operations allows readjusting the storage of water in the aquifers and surface reservoirs, so that the system can be prepared against droughts (perfectly hedging storage), reducing spills and losses in an optimal way. The high percentage reduction in scarcity cost is due to the reduction in scarcity, particularly for uses with higher economic value. The perfect foresight inherent in this deterministic optimization overestimates the efficiency

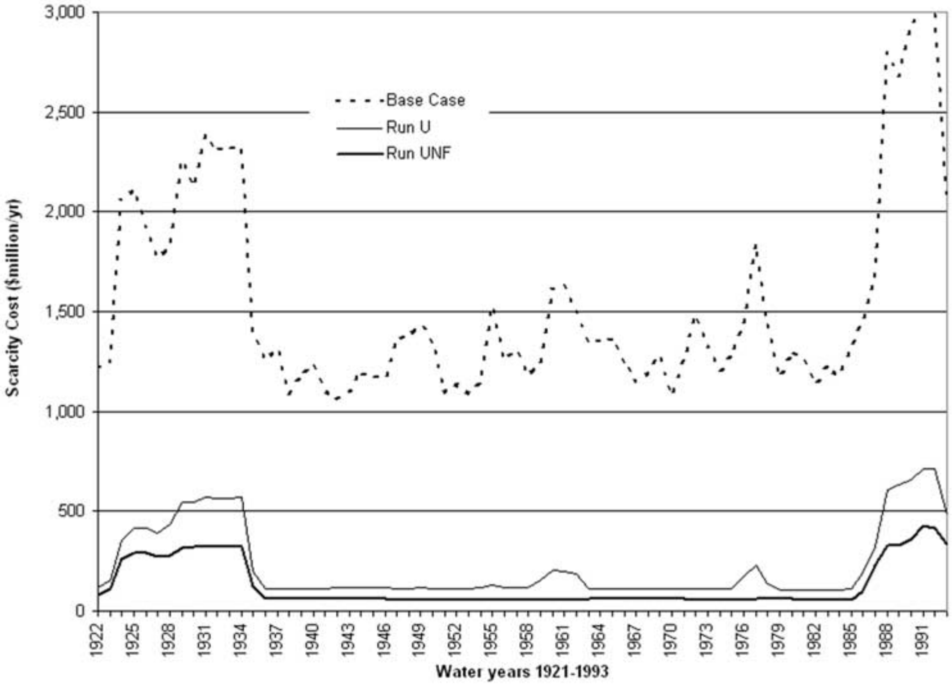

Figure 2. Annual scarcity cost ($ million/yr) for southern California.

attained, and so it is an upper bound value on what could actually be achieved with realistic hydrologic forecasts.

[25] The results of run UNF reveal the benefits of proposed new conjunctive use facilities. The change in scarcity volume compared to alternative U is insignificant, but scarcity cost is reduced by a further 44%. The additional groundwater storage capacity allows better regulation of flows in time, improving use of water in the system and its temporal reallocation to reduce costs. Operating cost is almost equal for both alternatives. Since the aquifers along the Colorado River Aqueduct play no role in the operation of the system, as discussed later, implementation of the conjunctive use program in GW-Kern, together with the artificial recharge program in the Lower Coachella Valley, are worth $98 million/year on average (net additional benefit from run U to run UNF).

[26] Figure 2 shows the stream of annual scarcity costs during the 72-year period for the different alternatives, revealing the economic differences between current operating policies and economically-based water allocation (alternatives BC and U). Differences between alternatives U and UNF correspond to the annual benefits of conjunctive use with the new facilities. Scarcity volume is similar for the three alternatives, except during drought periods, but scarcity cost in the base case far exceeds the unconstrained run's scarcity costs over the whole period. The reduction of scarcity cost during droughts is greater in run UNF, due to the additional storage capacity in the system.

5.1. Conjunctive Use's Economic Value to Water Users

[27] Although the region gains significant benefits from flexible conjunctive use and water allocation, and these benefits increase with additional conjunctive use facilities, the overall benefits are not equally shared among economic sectors (Table 2).

Table 2. Water Target, Deliveries, Scarcity, and Scarcity Cost by User

	Maximum, mcm/yr	Delivery, mcm/yr, BC	ΔDelivery, mcm/yr		Scarcity, mcm/yr			Scarcity Cost, $ million/yr		
			U-BC	UNF-BC	BC	U	UNF	BC	U	UNF
Palo Verde	973	816	−183	−197	157	340	354	1	9.4	10
Coachella Agriculture	241	241	−18	−18	0.0	17	17	0	0.9	1
Imperial	3,370	3,100	−288	−411	270	558	681	5	21.0	32
Total Agriculture	4,584	4,157	−488	−625	427	915	1,052	7	31	43
Central MWD	4,602	4,341	156	194	261	105	66	207	75.7	44
E&W MWD	913	867	28	35	46	18	12	42	13.6	8
San Diego	1,219	1,175	24	32	44	20	12	40	15.4	9
San Bernardino	349	341	−2	2	8	10	6	5	4.7	3
Antelope Valley	342	223	107	113	119	11	6	201	8.5	4
Castaic Lake	158	51	97	101	107	10	6	528	5.8	3
Mojave Urban	434	266	144	155	168	24	13	200	10.5	5
Coachella Urban	741	465	168	254	276	108	22	311	61.0	8
Total Urban	8,758	7,730	722	886	1,028	306	142	1,534	195	84
Total	13,341	11,886	234	260	1,455	1,221	1,195	1,541	226	127

[28] Palo Verde and Imperial agricultural regions see the largest decreases in deliveries from the base case. Almost all urban areas see increased deliveries. The most promising transactions are from agricultural areas on the Colorado River to the urban regions. With new conjunctive use facilities, 123 mcm/yr of additional water is transferred from the Palo Verde and Imperial irrigation districts to Coachella via the Coachella's branch of the All American Canal. Increased in recharge in the Lower Coachella Valley allows increased groundwater use and reduces scarcity in Coachella. It also allows decreased use of CRA diversions for recharging the Upper Valley. The reduction in CRA's Coachella deliveries is transferred to other MWD demands, reducing their scarcity and releasing SWP water for San Bernardino, Antelope, Mojave, and Castaic users. The difference between the increased agricultural scarcity and reduced urban scarcity is due to higher return flows and reuse from urban deliveries. The role of groundwater storage north of the Tehachapi Mountains (GW-Kern) is mainly to redistribute water in time to mitigate the economic impacts of major droughts. The substantial storage capacity in GW-Kern allows the water gained from the increasing conjunctive use in Coachella to be stored for Coachella's use during severe droughts. The higher supply during the two major droughts (in run UNF over run U) reduces scarcity cost significantly.

[29] Demands with scarcity see an economic value for additional supplies. CALVIN reports marginal economic value at any time and location in the system of additional water from an external source. This value is the marginal willingness to pay (MWTP) at a location and hydrologic condition, and is a useful spatial and temporal indicator of economic potential for inter- and intraregional transfers. For each demand, the MWTP in each time step is driven by the slope of the demand's economic value at the delivered water quantity. Table 3 shows the MWTP for additional water for each run at each demand area. Since all demands experience scarcities, all demands have a positive MWTP, with urban users having much higher MWTP than agricultural users. Agriculture MWTP increases in the unconstrained runs, U and UNF, due to their increased scarcities from water transfers to urban demands. MWTP decreases for all urban users compared to the base case, reflecting decreased scarcities. The most significant reductions occur in Antelope and Castaic Lake, in which huge MWTP with current operation reflects the high marginal values of water in these areas under current high scarcities. Optimal operation of new conjunctive use facilities reduces MWTP for all urban demands, especially Coachella, which has a steep demand function (due to resorts and golf courses). In economic theory, economically optimal allocation is reached when all the demands have the same marginal net return (equimarginal principle). In this case the allocation is constrained by the physical infrastructure capacity, and operating costs may reduce marginal net returns. Return flow percentage and reuse cost also affect economic values in the system.

Table 3. Users' MWTP for Additional Water

	Average WTP, $/tcm			Maximum WTP, $/tcm		
	BC	U	UNF	BC	U	UNF
Agricultural demands						
Palo Verde	15	55	58	17	58	58
Coachella	0	50	50	0	50	50
Imperial	19	58	73	19	88	88
Urban demands						
Castaic Lake	8,509	358	202	16,598	1,071	843
San Bernardino	325	166	126	2,694	738	610
E & W MWD	679	238	185	3,306	1,106	827
Central MWD	749	263	193	1,779	1,075	888
Antelope Valley	2,117	358	202	2,542	1,071	843
San Diego	463	220	178	2,013	1,005	859
Coachella	1,215	726	297	1,584	859	480
Mojave	1,258	464	402	1,675	503	411

Table 4. Boundary Marginal Economic Value of Water[a]

	Positive Average, $/tcm			Maximum Value, $/tcm			Minimum Value, $/tcm		
Location	BC	U	UNF	BC	U	UNF	BC	U	UNF
SWP	1,838	148	89	2,265	634	433	1,010	−184	−178
LAA (Mono-Owens)	781	474	387	1,932	1,010	809	202	223	229
Colorado River	637	89	90	1,792	90	90	394	84	90

[a] Table 4 does not include hydropower benefit associated with the LAA, since the LAA is incorporated as an inflow in the base case, and it would not be comparable for the different runs.

[30] Dual values at the boundary regions represent the marginal willingness-to-pay for additional deliveries from each imported source, indicating the economic desirability of inter-regional water transfers. A flexible water market and conjunctive use (run U) significantly reduces MWTP for all imported sources (Table 4). New conjunctive use facilities (run UNF) further reduce MWTP for LAA and SWP water. The LAA average boundary value is highest in the unconstrained runs, reflecting better water quality and lower operating cost. Figure 3 displays the time series of marginal economic values of additional LAA water for each run. LAA water is especially valuable during the two major droughts (1929–1934 and 1987–1992). Flexible allocation and flexible conjunctive use in runs U and UNF significantly reduce the demand for increased LAA imports, especially during major droughts.

[31] In run BC, Colorado River water is allocated by the current "Law of the River". Additional water yields a high benefit, since it can be allocated to Coachella or MWD urban demands, with high economic scarcities. The average marginal value of Colorado River water ($637/tcm) is far from the willingness-to-pay for additional water in Coachella ($1,215/tcm) and Central MWD ($749/tcm), due to limited CRA capacity, when it binds. In the unconstrained runs, U and UNF, CRA capacity usually limits the supply to urban demands, so the marginal value of additional Colorado River water drops ($89/tcm), near the marginal-willingness-to-pay of Palo Verde and Imperial agriculture.

5.2. Environmental Flow Shadow Values

[32] Environmental demands are modeled in CALVIN as constraints (minimum streamflows, annual deliveries, or minimum storages). Shadow values for links with environmental constraints indicate the marginal opportunity costs of environmental requirements on agricultural and urban water users and hydropower generation, as well as operating costs. In this southern California model, environmental constraints include minimum streamflows into Mono Lake, minimum Mono Lake level, and diversions for Owens

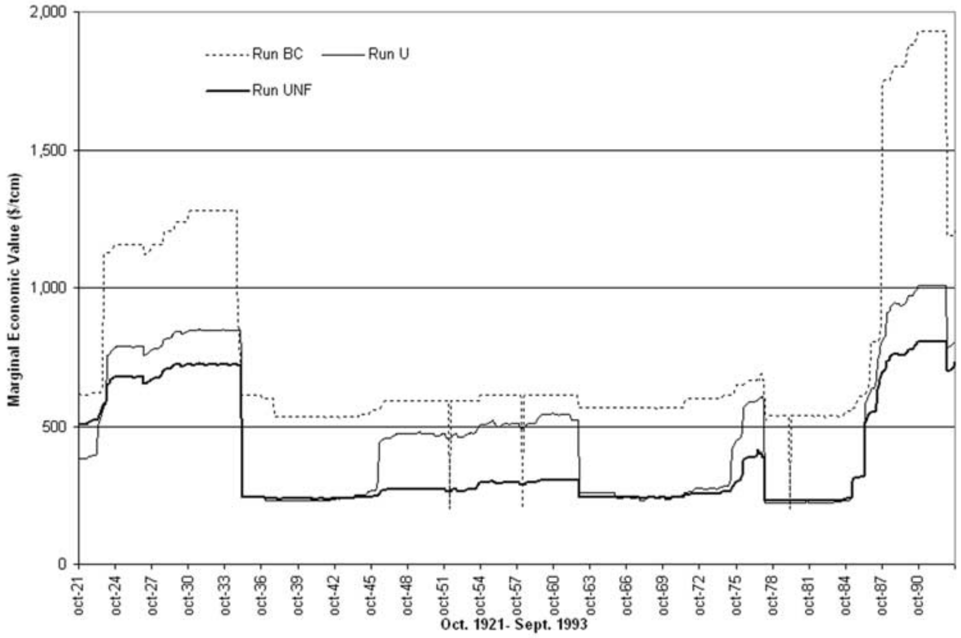

Figure 3. Marginal economic value of LA Aqueduct water.

Lake. The high shadow values for Mono Lake inflows and Owens Lake diversions (Table 5) reflect scarcity costs in Central MWD and the higher operating and opportunity costs of substitute water from SWP. The shadow values for Mono Lake inflows are higher because of lost hydropower benefits. In run UNF, shadow values decrease due to reductions in opportunity costs of alternative supplies, driven by scarcities.

6. Promising Operating Rules for Conjunctive Use

[33] Preliminary system operating rules for a large multipurpose multireservoir system can be inferred from deterministic optimization results based on long hydrologic records [*Lund and Ferreira*, 1996]. The goal of this research is not to derive operating rules for this complex system, but to discuss the economic advantages of optimal conjunctive use under flexible water allocations in southern California, and the added value of new conjunctive use infrastructure. Nevertheless, optimized conjunctive operation of surface and groundwater reservoirs suggests changes in the current operating policy that could improve overall system performance, and some preliminary operating rule ideas are presented.

[34] Figure 4 displays changes in total surface storage, showing greater over-year surface storage in run U than in run UNF, in which over-year storage is accomplished mainly by GW-Kern, as discussed in section 6.3. Figure 5 displays total groundwater storage; the system is more aggressively operated than in the constrained base case, due in part to perfect knowledge of future hydrology and lack of risk aversion. For the unconstrained runs, CALVIN suggests more aggressive pumping during the 1929–1934 drought, after which the average storage level is recovered, with more intensive recharge in preparation for the 1987–1992 drought. Comparison of Figures 4 and 5 indicates that most water storage for southern California is groundwater storage; groundwater average storage in run UNF is over twenty times greater than surface water average storage. The conjunctive use strategy with emphasis on cyclic long-term carry-over groundwater storage has been named as cyclic storage, and its potential benefits have been reported in the literature [*Thomas*, 1978; *Lettenmaier and Burges*, 1982]; the system becomes groundwater storage dominated and the operating issues are largely distributions to and from the groundwater reservoirs.

6.1. Conjunctive Use in Coachella Subsystem

[35] Figure 6 shows the time series of annual groundwater recharge in the Coachella subsystem with CRA water. In run UNF, artificial recharge in the Lower Coachella Valley is always at full capacity, 118 mcm/yr, since the CRA is full and urban demand has a much higher marginal willingness to pay than Imperial and Palo Verde agricultural demands. Increased recharge in the Lower Valley allows increased groundwater utilization, reducing water scarcity in Coachella (by 86 mcm/yr), and decreasing CRA diversion for recharging the Upper Valley (74 mcm/yr). The multiplier effect of increased groundwater return flows from increased supply increases water reuse through groundwater recharge and pumping, and through direct wastewater reuse. CRA deliveries to Coachella for recharge in the Upper Valley cease during major droughts, when Coachella urban demand is served by intensive use of

Table 5. Annual Requirements and Shadow Values on Environmental Flows

Location	Annual Requirement, mcm/yr	Average, $/tcm		Maximum Value, $/tcm	
		U	UNF	U	UNF
Mono Lake inflows	91	739	652	1,619	1,375
Owens Lake dust mitigation	49	570	486	1,155	947

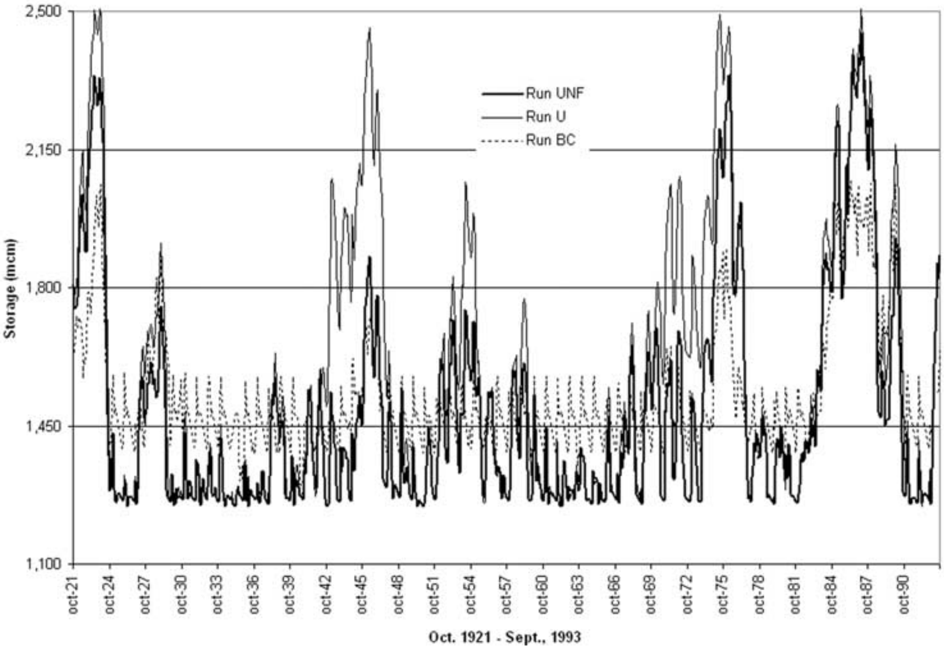

Figure 4. Southern California total monthly surface storage.

previously accumulated groundwater. The reduction in CRA's Urban Coachella supplies is transferred to MWD demands, releasing 25 mcm/yr of SWP water for other users.

6.2. Conjunctive Use Along the Colorado River Aqueduct

[36] In both unconstrained operation runs, U and UNF, additional groundwater storage along the Colorado River Aqueduct is not used. The reason is that MWD can store Colorado River water surplus in its Diamond Valley Lake, and Coachella Urban does not need additional storage capacity, since it can recharge the aquifer in advance to cover droughts. This ability is artificially aided by the model's hydrologic foresight. Without such foresight, Coachella Urban would probably want to maintain greater groundwater reserves or access to CRA supplies. Under foresight, flexible water exchange, Coachella conjunctive use facilities, and additional groundwater storage capacity in GW-Kern, there is no benefit from implementing the Cadiz, Upper Chuckwalla or Hayfield conjunctive use projects. As long as water transfers from Colorado River agricultural users fill the CRA, there is no value to storing water in

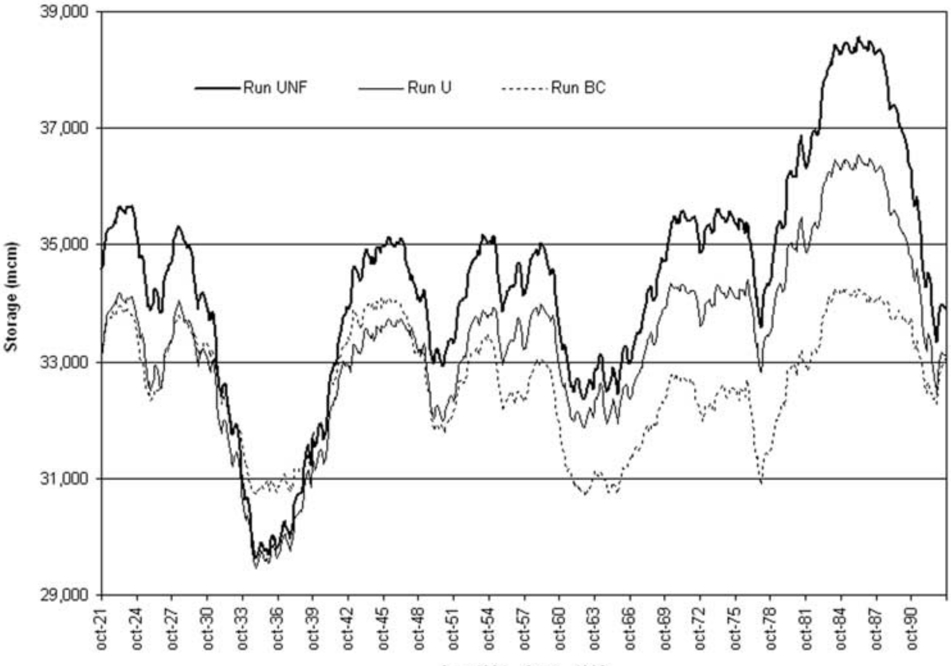

Figure 5. Southern California total monthly groundwater storage.

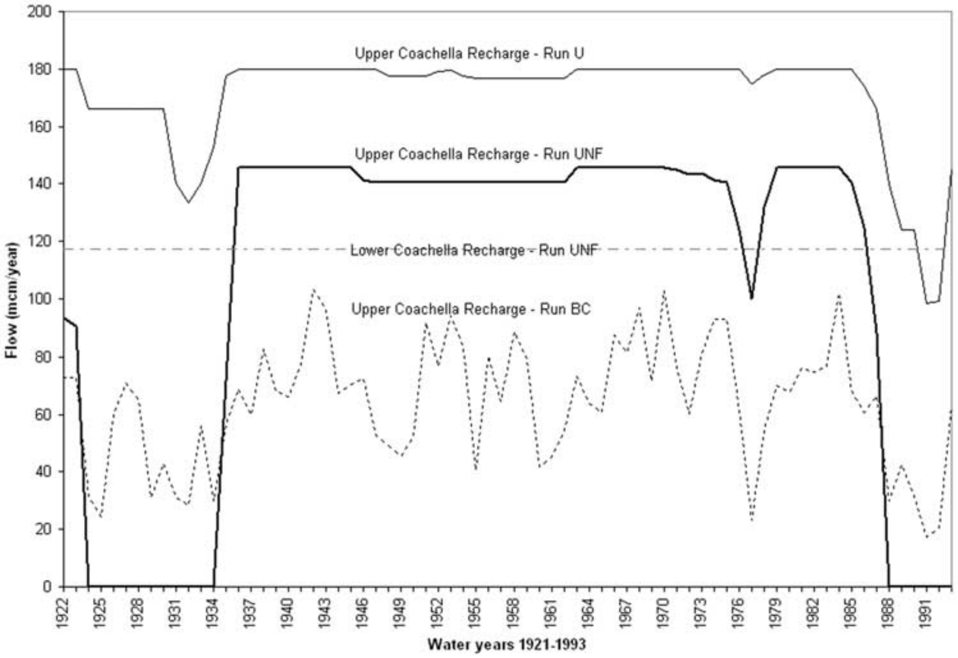

Figure 6. Coachella Valley annual groundwater recharge.

aquifers which rely on CRA conveyance, since recharge or discharge of these aquifers would reduce the CRA capacity to convey water transferred from agriculture. Use of conjunctive use locations tributary to CRA would require greater CRA conveyance capacity under these conditions.

6.3. Reservoir Operations

6.3.1. Diamond Valley Reservoir

[37] MWD's off-stream Diamond Valley Reservoir is the main surface storage in the system (987 mcm capacity). As Figure 7 shows, in run UNF Diamond Valley Reservoir's role is reduced to carryover storage in the 3–5 years before the three most severe droughts, remaining in most years at almost the inactive emergency storage level. Although Diamond Valley provides the main carryover storage in runs BC and U, in run UNF carryover storage is moved to GW-Kern. Long-term groundwater storage prevents evaporation losses, which are significant for Diamond Valley Reservoir (evaporation and losses occur only once during aquifer recharge, while evaporation in surface reservoirs depletes storage each month). Increased conjunctive use storage in run UNF diminishes the importance of long-term

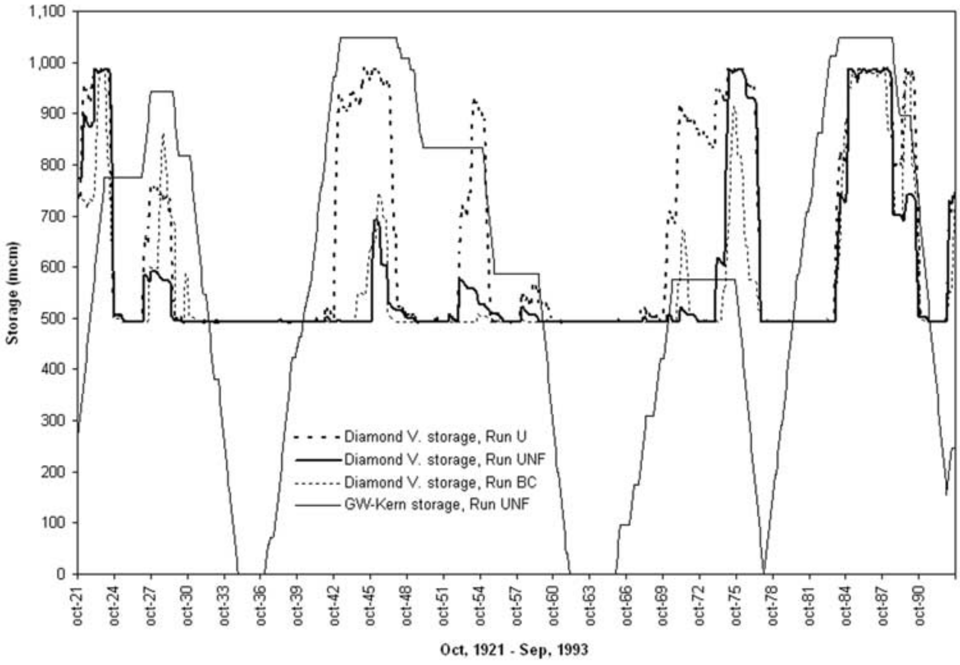

Figure 7. Diamond Valley and groundwater-Kern monthly storage.

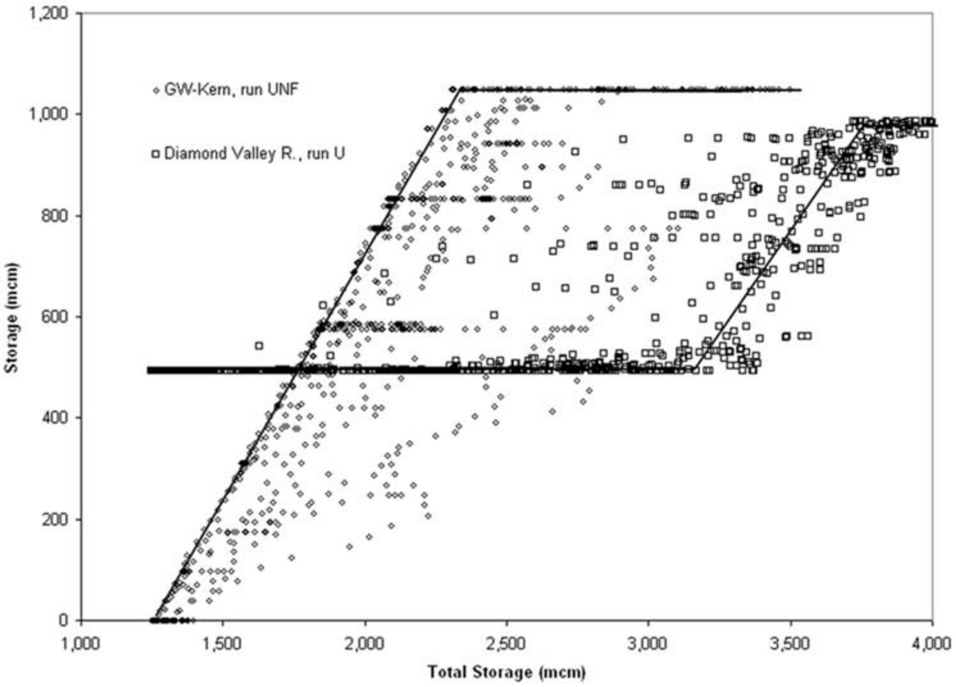

Figure 8. Diamond Valley and Kern groundwater basin monthly storage versus total storage.

storage in Diamond Valley for storing SWP and CRA water prior to the major droughts.

6.3.2. GW-Kern (Run UNF)

[38] Under alternative UNF, the two main reservoirs of the system, Kern Groundwater Basin and Diamond Valley Reservoir, are complementary. Storage in Kern is long-term carryover storage to mitigate droughts (Figure 7). Diamond Valley Reservoir captures part of the CRA flow released before the drought thanks to Coachella conjunctive use, and this extra storage supplies MWD demands. The groundwater operation rule requires little foresight.

6.4. Distribution of Storage Among Reservoirs

[39] Results show a pattern of balancing total storage between the two main reservoirs, Kern Groundwater Basin and Diamond Valley Reservoir, in runs U and UNF (Figure 8). In run UNF, maximum storage levels correspond to the situation prior to droughts. The initial reductions in total system storage from maximum levels come from storage in other smaller surface and groundwater reservoirs. GW-Kern storage is decreased as system-wide storage falls below 2344 mcm, with system storage reductions coming almost entirely from GW-Kern. The groundwater basin becomes "empty" at the end of severe droughts (Figures 7 and 8) as total storage falls below 1233 mcm.

[40] In run U, the pattern of the balancing rule for the Diamond Valley Reservoir storage approaches a piecewise linear allocation (Figure 8). It is retained as full or nearly full for early reductions in total system storage. As total storage falls below 3,700 mcm, storage in the reservoir is decreased until the minimum storage pool is reached. Refill storage allocation follows this rule in reverse.

7. Infrastructure Expansion

[41] CALVIN reports shadow values on storage and conveyance capacity constraints, revealing additional benefits if a capacity is increased. Since there are lower and upper bound constraints, negative shadow values are reported when the lower bound is binding, indicating that the system will benefit from a reduction in the lower bound. If the lower bound is zero in a conveyance facility, negative shadow values indicate an economic value for a reverse flow. Negative shadow values for a dead or emergency storage pool indicate an economic value to encroach into this water.

7.1. Marginal Value of Storage Capacity Expansion

[42] Table 6 displays the expected and maximum value of expanding each surface storage facility. In run U, the highest expected value corresponds to LAA storage facilities, whose water has the highest quality and energy value. Additional surface storage capacity decreases in value with

Table 6. Marginal Economic Value of Reservoir Capacity Expansion

	Average Annual Value,[a] K$/tcm		Maximum, K$/tcm/month	
Surface Reservoir	U	UNF	U	UNF
Silverwood Lake	22.6	11.9	261.6	195.8
Lake Perris	15.9	7.3	261.0	195.3
Pyramid Lake	16.4	7.8	261.2	195.5
Castaic Lake	16.7	8.1	262.0	196.2
Aggregated Los Angeles Reservoir	8.7	5.8	290.5	288.4
Grant Lake	26.4	23.6	431.9	434.4
Long Valley Reservoir (Lake Crowley)	8.7	5.8	290.0	287.8
Lake Mathews of MWDSC	14.7	6.4	258.8	193.3
Lake Skinner	14.9	9.5	256.7	217.1
Diamond Valley Reservoir	14.5	6.0	261.4	195.6

[a] Considered as the average of the maximum monthly shadow values of each hydrologic year.

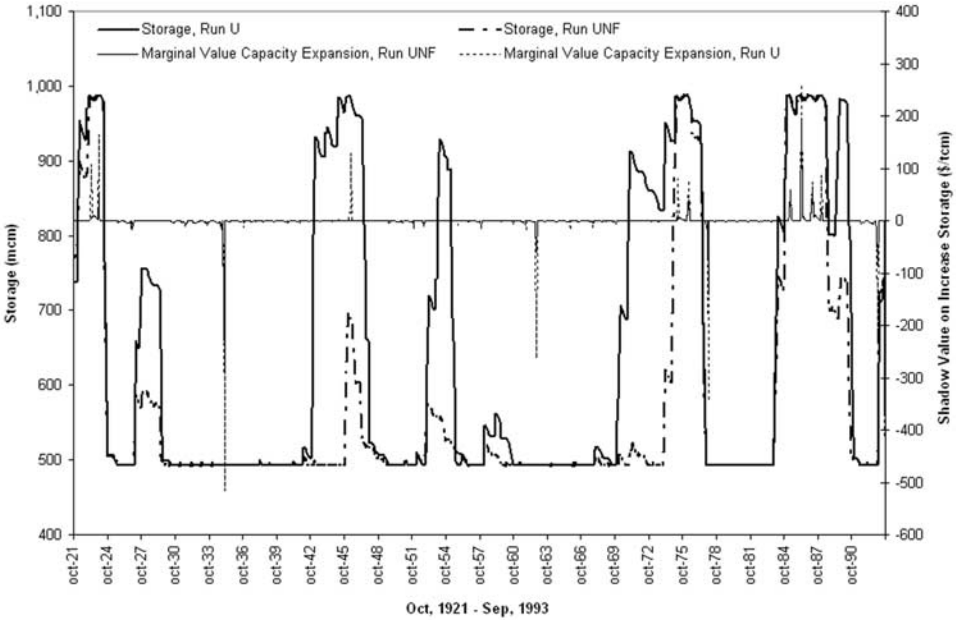

Figure 9. Diamond Valley storage and capacity shadow values, run U and run UNF.

run UNF, due to the extra storage capacity in the Kern groundwater basin.

[43] Figure 9 displays the storage and shadow value time series for Diamond Valley Reservoir, an off-stream reservoir with high operating cost ($17/tcm). In run U, positive shadow values occur before droughts, when the system tries to store as much water as possible and storage capacity binds. Negative shadow values emerge toward the end of droughts, when the lower capacity binds and the system would benefit from drawing water from the minimum pool. In run UNF, Diamond Valley Lake usually remains at the minimum level, with shadow values substantially reduced due to additional storage of SWP water in Kern groundwater.

[44] Figure 10 shows Kern groundwater operations for run UNF, revealing its long-term drawdown and refill operations to accommodate droughts, as well as its adequate storage capacity, evidenced by low and infrequent shadow values on capacity constraints. Without perfect hydrologic foresight, drought reserve storage will have a higher economic value than those indicated by these shadow prices [*Draper*, 2001].

7.2. Marginal Value of Conveyance Capacity Expansion

7.2.1. Mojave Pipeline

[45] Figure 11 shows the shadow value time series for expanding the Mojave pipeline's capacity, with a high average positive shadow value (364 $/tcm/month in run U).

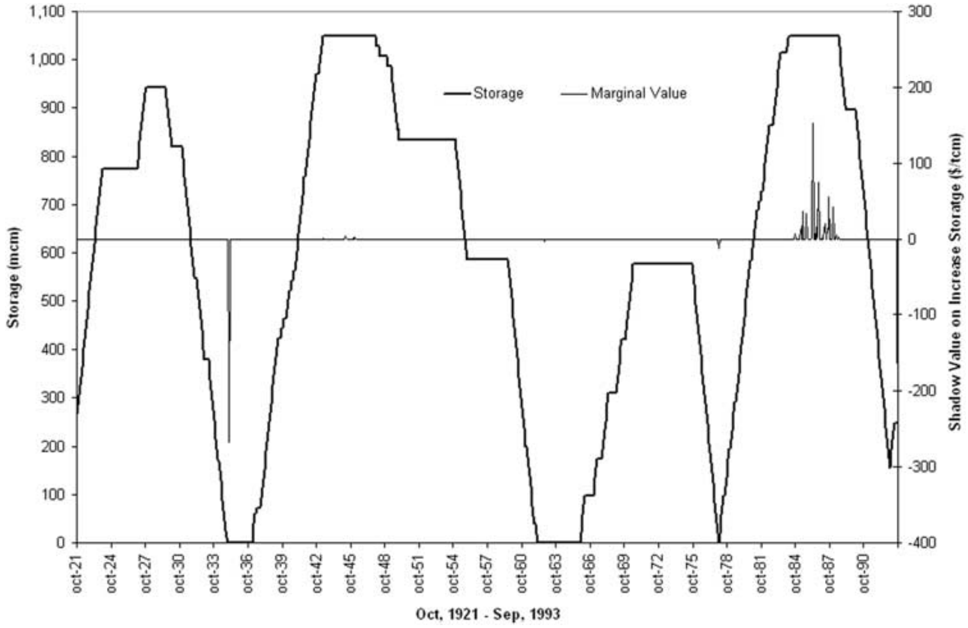

Figure 10. Kern Groundwater Basin storage and capacity shadow values, run UNF.

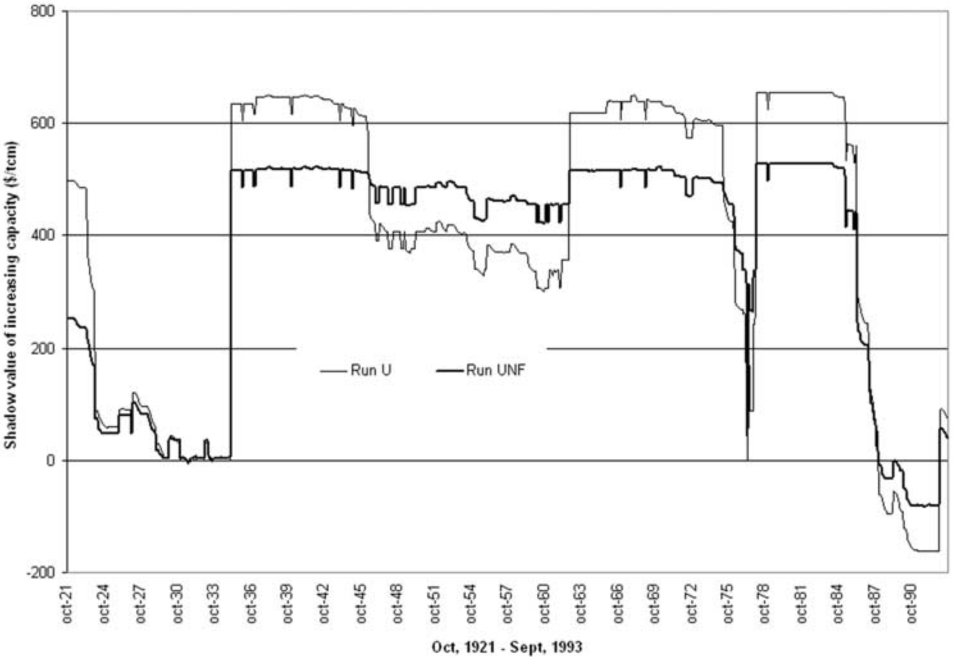

Figure 11. Shadow values on Mojave pipeline capacity.

During major droughts, this conveyance capacity is not binding and shadow values become zero. For the last drought (1987–1992), negative shadow values indicate that the lower bound is binding and the system would benefit from exporting water from Mojave, using the Mojave Basin as a storage facility for the entire system. The reduction in shadow values for run UNF arises from additional GW-Kern storage.

7.2.2. Conjunctive Use in Coachella: Artificial Recharge

[46] Figure 12 shows that artificial recharge capacity in the Upper Coachella Valley significantly reduces shadow values in run UNF. Increased conjunctive use operation in the Coachella system (including recharge in the Lower Valley) in run UNF substantially lessens scarcity in Coachella. Although recharge capacity still usually binds, the marginal economic benefit of expanding recharge capacity is reduced.

7.2.3. Colorado River Aqueduct

[47] The Colorado River Aqueduct capacity binds during most months in the period of analysis. Although the shadow values' temporal pattern is similar in both runs, the values are significantly lower in run UNF, due to the reduction in scarcities and scarcity cost in run UNF (Figure 13).

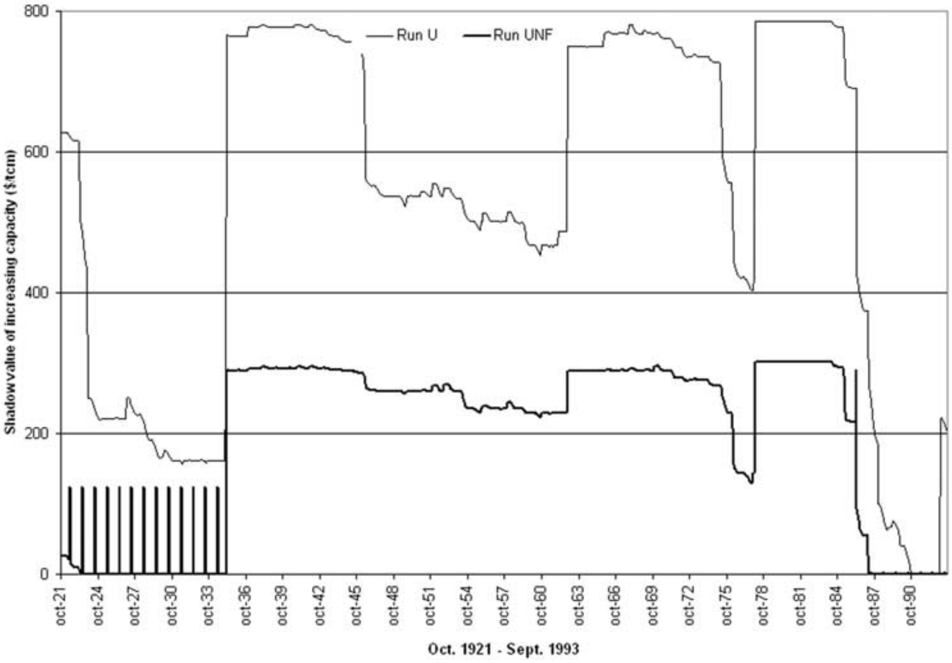

Figure 12. Shadow values on artificial recharge in the Upper Coachella Valley.

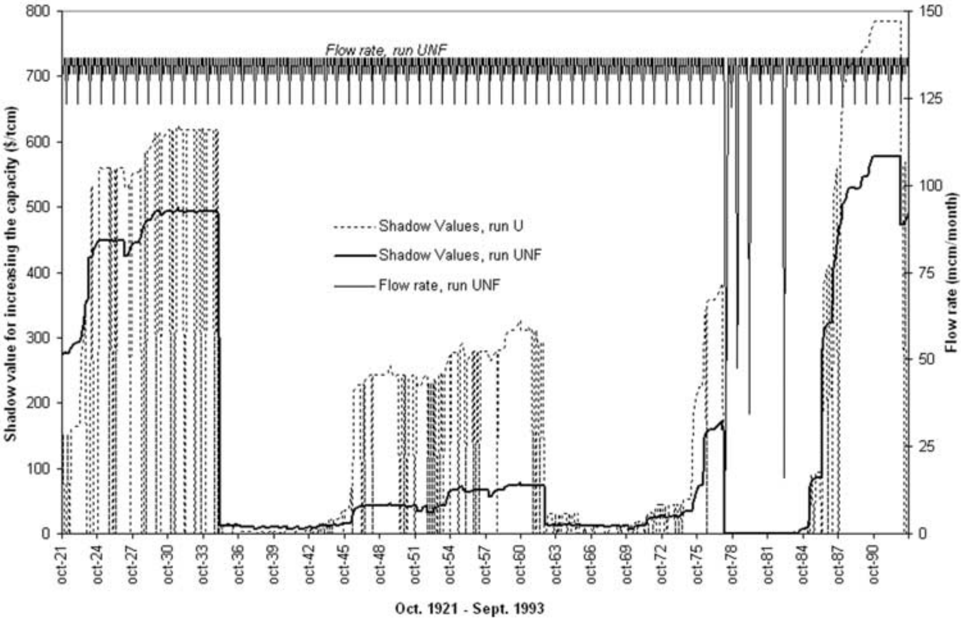

Figure 13. Shadow values on the capacity constraint in the Colorado River Aqueduct.

7.2.4. Kern Groundwater Basin Pumping and Recharge

[48] Operation of the Kern groundwater basin differs from most aquifers in the system, since it is used for long-term storage. Expanding recharge capacity is only worthwhile early in the period of analysis, when the system is trying to recharge as much water as possible (Figure 14). Expanding pumping capacity is especially worthwhile during the 1976–1977 and 1987–1992 droughts. Average positive shadow values on capacity are very low, \$6.5/tcm/month for pumping, and \$4.9/tcm/month for recharge. There is little economic incentive to expand recharge, pumping or storage capacity for the Kern groundwater basin, although these values would increase with imperfect foresight.

8. Limitations and Possible Improvements

[49] Limitations of the CALVIN approach are discussed elsewhere [*Jenkins et al.*, 2001; *Draper et al.*, 2003]. Although the model presented can be useful for general investigations of conjunctive use potential in southern

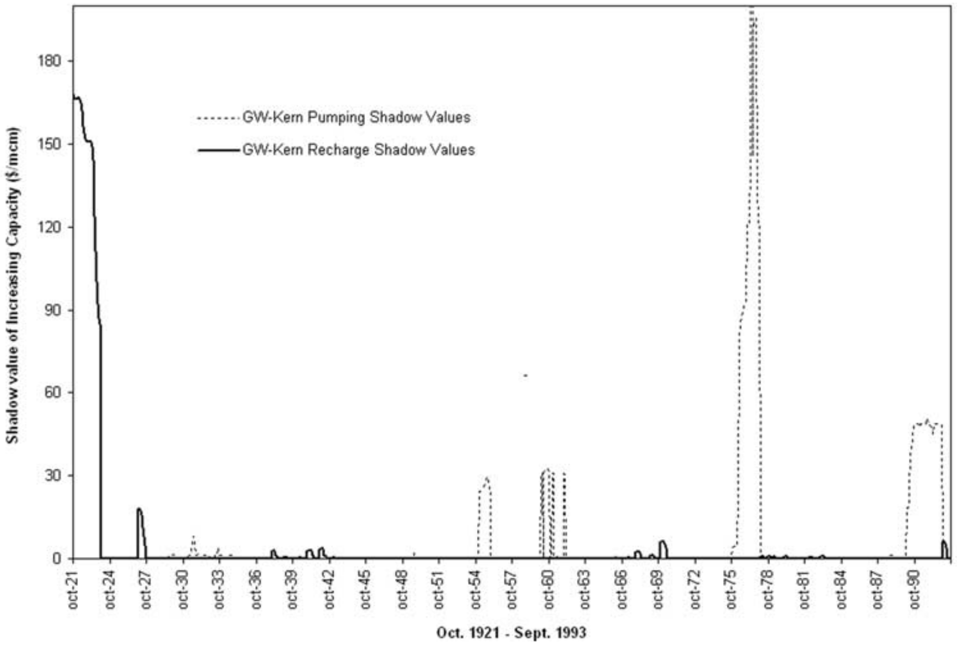

Figure 14. Shadow values on Pumping and Artificial Recharge in Kern groundwater basin.

California, the representation of the system could provide more accurate outputs with some refinements.

8.1. Perfect Foresight

[50] The model optimizes system operation over the entire 72-year period simultaneously. Therefore the model optimizes with perfect knowledge of future inflows, rarely a realistic situation. Conjunctive reservoir and aquifer operations are adjusted in perfect anticipation of wet years and droughts, increasing carryover storage prior to droughts (aggressive hedging) and little carryover storage prior to wet years (lack of hedging). Perfect foresight understates the value of new storage and conveyance capacity, and can underestimate actual scarcity and scarcity cost. *Draper* [2001] proposed an implicit stochastic model with limited foresight using an optimized carryover storage value function. He found that the importance of perfect foresight generally decreases significantly with greater amounts of over-year storage available and that integrated conjunctive use reduces greatly the effects of perfect foresight. *Newlin et al.* [2002] found the effects of perfect foresight on overall performance to be small for this system, since improved performance comes predominantly from consistent operation and allocation changes that do not require hydrologic foresight.

8.2. Perfect Institutional Flexibility

[51] The assumptions of flexible conjunctive use operations and water allocation diverge somewhat from managerial and institutional reality. However, they allow the investigation of promising alternatives of operation of the system, and identify the regional and local benefits associated with these alternatives. Transaction costs, delays, and risks in operations and allocations are often high. Overall, the optimization results support most water management policies of southern California's urban agencies [*MWDSC*, 2000, 2002].

8.3. Groundwater Representation

[52] Deep percolation from conveyance losses and rainfall, and stream-aquifer and inter-basin interactions are preprocessed as a fixed time series of groundwater inflows and thus not dynamically represented in CALVIN. Use of fixed groundwater pumping costs neglects and effects of variable pumping costs on benefits and system operation. Since groundwater is more aggressively operated in the alternatives studied, changes in pumping cost might be significant. Besides the substantial additional computation time that modeling variable pumping cost would require with the current solver, lack of reliable and consistent data hinder its implementation [*Jenkins et al.*, 2001].

8.4. Simplified Representation of Water Demands and Deliveries

[53] Modeling of demands and water deliveries requires many assumptions, discussed in detail elsewhere [*Jenkins et al.*, 2001, 2003]. The lack of empirical economic data hinders better economic representation of demands.

9. Conclusions

[54] Considering the limitations of this modeling approach, the modeling results lead to several conclusions.

[55] 1. Flexible water allocation (such as water markets), together with improved conjunctive use operation of surface and groundwater, can reduce scarcity and scarcity costs drastically in southern California. Small reallocations of water to demands with higher economic values can substantially decrease regional scarcity cost. The most promising transfers come from the agricultural regions on the Colorado River to urban demands, limited by the capacity of the Colorado River Aqueduct.

[56] 2. Additional conjunctive use storage and recharge capacities under flexible water allocation (water transfers) can generate substantial additional benefits for the region. Conjunctive use adds operational flexibility needed to take better advantage of water transfers, and transfers provide the allocation flexibility needed to take economical advantage of conjunctive use. The studied conjunctive use projects could produce a net average benefit as high as \$98 million/year.

[57] 3. Additional groundwater storage along the CRA (Cadiz, Hayfield, and Upper Chuckwalla) shows no benefit to the region, primarily because there is not surplus conveyance capacity in the CRA to recharge and withdraw water from these facilities. It is more economical to use CRA capacity for transfers of water directly from the Colorado River to urban users. It was assumed there were no noneconomic limits (apart from physical capacity constraints) on the ability to transfer water from Colorado River agricultural users to urban users.

[58] 4. Flexible operation of the system with conjunctive use reduces reliance on imported sources. Once the CRA is operated at full capacity, little economic incentive exits to increase California's supply from the Colorado River, given the low marginal willingness-to-pay for additional water for agricultural demands.

[59] 5. The results for optimal flexible conjunctive use suggest operating rules for the system, especially in balancing storage between the Kern groundwater basin and Diamond Valley Lake.

[60] 6. The highest marginal economic value of storage capacity expansion is for LAA storage facilities, due to high water quality and power values. Substantial benefits exist for expanding conveyance CRA capacity. Important benefits also exist from expanding other facilities (e.g., Mojave pipeline). Flexible allocation and increased conjunctive use capacity substantially reduce the marginal values of facility expansions.

[61] 7. Despite the limitations of deterministic optimization models, they can produce useful insights for improving operation and management of systems that are too complex for probabilistically explicit optimization. These insights are subject to testing and refinement through more detailed simulation modeling and operating experience. Consideration of uncertainty, especially regarding capacity decisions contingent on long-term uncertain demand growth, and valuation of the effect on results of limited hydrologic foresight and more risk averse system operations would be interesting extensions of this work.

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