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Economic Costs and Adaptations for Alternative Regulations of California's Sacramento–San Joaquin Delta

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ABSTRACT

Water exports from California's Sacramento–San Joaquin Delta are an environmental concern because they reduce net outflows of fresh water from the Delta, and can entrain fish and disrupt flows within the Delta. If exports were no longer pumped from within the Delta, the regulatory issue becomes one of maintaining appropriate flows into and out of the Delta. This paper presents the results of two sets of hydro-economic optimization modeling runs, which were developed to represent a range of modified Delta operations and their economic and operational effects on California's water supply system. The first set of runs represents decreasing export capacity from the Delta. The second set increases minimum net Delta outflow (MNDO) requirements. The hydro-economic model seeks the least–cost statewide water management scheme for water supply, including a wide range of resources and water management options. Results show that reducing exports or increasing MNDO requirements increase annual average statewide water scarcity, scarcity costs, and operating costs (from greater use of desalination, wastewater recycling, water treatment, and pumping). Effects of reduced exports are especially concentrated in agricultural communities in the southern Central Valley because of their loss of access to overall water supply exports and their ability to transfer remaining water to southern California. Increased outflow requirements increase water scarcity and associated costs throughout California. For an equivalent amount of average Delta outflows, statewide costs increase more rapidly when exports alone are reduced than when minimum outflow requirements are increased and effects are more widely distributed statewide.

KEYWORDS

water resources management, adaptation, water supply, water exports, Sacramento–San Joaquin Delta, California, CALVIN.

INTRODUCTION

The costs and flexibility of water systems adapting to changes in environmental regulations is an important policy and planning issue. The economic and environmental effects of different forms of regulation, including operator and societal adaptations, can now often be better understood using hydro-economic system modeling (Harou and others 2009). Hydro-economic models blend traditional hydrologic or

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water operations models (Yeh 1985; Draper and others 2004; Labadie 2004; Yates and others 2009) with economic models of water system performance (DWR 2010). Water exports from California's Sacramento–San Joaquin Delta are an important supply source to the Bay Area, southern Central Valley, and Southern California, providing drinking water to roughly two-thirds of all Californians, as well as irrigation water to millions of hectares of farmland (Lund and others 2007, 2010). These exports have become a central concern for the environmental health of the Delta because of dramatic declines in some native fish species in recent years. For several decades, various flow requirements and salinity standards at specific times of the year have regulated exports to protect fish. In December 2007, a ruling by the United States District Court, Eastern District of California (the Wanger Decision) further restricted flows from the export pumps at the southern edge of the Delta to reduce the risk of entraining delta smelt (*Hypomesus transpacificus*), a species listed under both the federal and state endangered species acts.[1] At about the same time, the state-appointed Delta Vision Blue Ribbon Task Force (the Task Force) released its strategic vision for the Delta (Isenberg and others 2008), echoing the views of many environmental advocates in arguing to consider export reductions. The Task Force and others also acknowledged that upstream diversions from the Sacramento and San Joaquin river watersheds are a significant drain on Delta flows and should contribute to providing additional flows into the Delta (Lund and others 2007, 2010).

Reducing exports and increasing flows to the Delta are related, but distinct, regulatory tools. Directly targeting export reductions helps avoid fish entrainment and other problems created by altered flows within the Delta, where exports are drawn through Delta channels to the pumps (Figure 1). If exports are instead diverted upstream and taken around the Delta through a peripheral canal, the role of the pumps in the southern Delta is reduced, and the regulatory issue becomes one of maintaining appropriate flows into the Delta. Regulatory flows are typically measured as net outflows from the Delta to the ocean or net Delta outflows. In addition to potential environmental benefits, increased net Delta outflows could be sought to maintain salinity standards for agricultural and urban users within the Delta in the face of sea level rise, which will likely push salinity from the ocean and Bay further into the Delta (Fleenor and others 2008). Although restricting exports can be used to increase net Delta outflows, this objective also can be attained more directly by requiring increased minimum net Delta outflows (MNDOs). Directly regulating Delta outflows versus reducing or eliminating exports could provide additional flexibility statewide because upstream diverters in the Sacramento Valley can lease or sell some of their water to exporters.

This paper explores the implications of these two regulatory strategies—export restrictions and MNDO increases—for California's economy and for water users in different parts of the state. This paper also explores the response of water users to increased Delta regulations, including adjustments to their water supply portfolio with tools such as transfers, groundwater banking, recycling, desalination, and conservation. Finally, this paper assesses how these regulations change the costs of providing water for environmental mitigation in different parts of the state, and how they affect the attractiveness of different infrastructure investments, including new conveyance and new surface and groundwater storage facilities.

MODELING APPROACH

To provide a more integrated understanding of the statewide economic costs and adaptations available for these regulatory alternatives, a large-scale economic–engineering optimization model, CALVIN, was employed (*http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/*). The CALVIN model has been presented elsewhere, so only a brief discussion follows.

The CALVIN Model

The California Value Integrated Network (CALVIN) is a generalized network flow-based economic–engi-

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[1] Natural Resources Defense Council, et al. v. Kempthorne, Findings of Fact and Conclusions of Law Re. Interim Remedies Re: Delta Smelt ESA Remand and Reconsultation, United States District Court, Eastern District of California, 1:05-cv-1207 OWW GSA (2007).

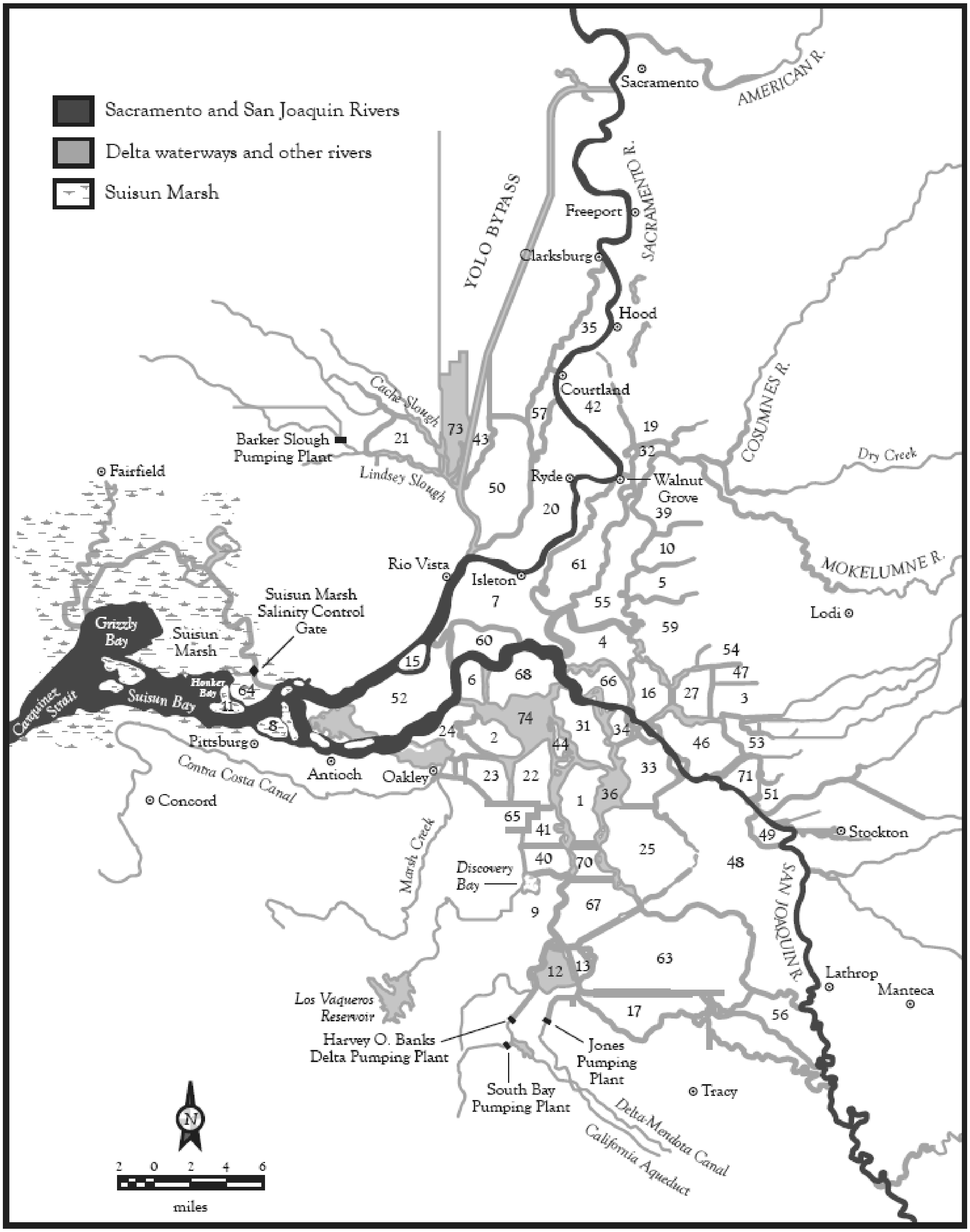

Figure 1 Map of Delta islands with island numbers indicated. Source: Lund and others 2010.

neering optimization model of California's intertied water supply system, including 92% of California's population and 88% of the state's irrigated lands (Figure 2). It includes the major facilities of the State Water Project (SWP) and the Central Valley Project (CVP), along with many regional and local facilities. In all, the model includes 53 surface water reservoirs and 31 groundwater basins. CALVIN's economic calculations cover 24 agricultural areas and 30 urban areas. CALVIN has been used previously to examine various water-management problems in California (Jenkins and others 2001, 2004; Newlin and others 2002; Draper and others 2003; Tanaka and others 2003, 2006; Pulido–Velázquez and others 2004; Null and Lund 2006; Lund and others 2007; Medellín–Azuara and others 2008; Connell 2009; Harou and others 2010). The model expands on the economic model of Vaux and Howitt (1984), with a broader representation of management options and environmental and physical constraints common in more traditional optimization models (Becker and others 1976; Marino and Loaiciga 1985; Lefkoff and Kendal 1996).

Optimization models are well suited to explore alternatives and identify those with more promising performance (Mirchi and others 2010). CALVIN seeks to minimize operating costs and economic losses for urban and agricultural users throughout California's water system, over the range of historical hydrology (water years 1921–1993). CALVIN also has been used

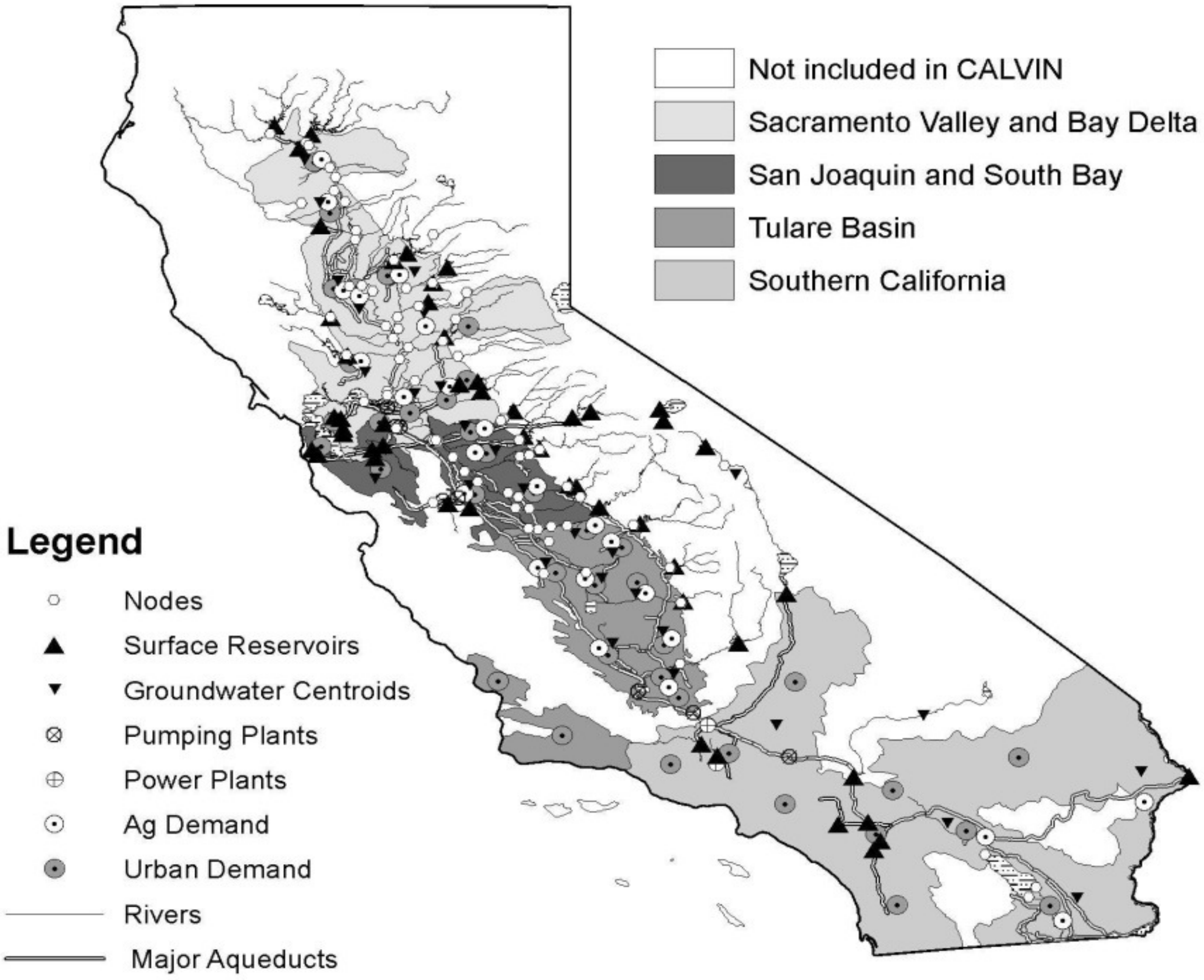

Figure 2 Demand areas and major inflows and facilities represented in CALVIN. Source: Medellín-Azuara and others 2008.

to explore outcomes under hydrology influenced by different forms of climate change (Tanaka and others 2006; Medellín–Azuara and others 2008; Connell 2009; Harou and others 2010). Although climate change is not analyzed for these CALVIN results, some indications of how the results might be affected by climate change are provided in the discussion of the results. Previous studies indicate that Delta exports often become more economically important with climate warming, and for drier climates in particular.

CALVIN uses a generalized network flow optimization solver for water resources systems, Hydrological Engineering Center—Prescriptive Reservoir Model (HEC–PRM), to find the least-cost solution with specified constraints (HEC 1991). The specified constraints in CALVIN represent the physical and institutional limits imposed on the water system (e.g., physical limits on infrastructure capacity or regulatory limits on the use of these facilities). CALVIN requires many physical and economic input parameters to characterize California's water system. Physical parameters include infrastructure capacity (such as canals and pumping plants), environmental requirements (such as minimum instream flows and wildlife refuge requirements), operating requirements (such as flood storage in reservoirs), return flow coefficients, and inflows into groundwater and surface water reservoirs. Economic parameters include urban and agricultural water demand functions, as well as operating costs for water treatment, conveyance, and hydropower facilities. These inputs are detailed in Jenkins and others (2001).

The results presented here simulate the level of development in the year 2050, with a projected population of 65 million (up from 39 million in 2008) (Department of Finance 2007; Medellín–Azuara and others 2008). Urban water demands were developed based on year 2020 per capita demands by county and population estimated by the California Department of Water Resources (DWR) Bulletin 160–98, and by estimates from Metropolitan Water District of Southern California data for Southern California urban areas (Jenkins 2000; Jenkins and others 2003), scaled to the estimated 2050 population. The 2050 agricultural water demands and values were developed from results from the Statewide Agricultural Production Model (SWAP) (Howitt and others 1999). CALVIN's economic data are in 1995 dollars, but all costs reported here have been updated to 2008 dollars using the *Engineering News-Record* multiplier of 1.48.

In addition to current facilities, the model runs presented herein include some additional facilities expected to be completed by 2050, including several new interties which are planned or are underway (e.g., Freeport Project and the Hayward Intertie). Likewise, urban coastal areas were assumed to have access to desalted seawater at a cost of $1,135 per thousand cubic meter (TCM) in 1995 dollars ($1,680 per TCM in 2008 dollars). All urban areas were assumed to have access to up to 50% of their wastewater flows as recycled water, at a cost of $811 per TCM (in 1995 dollars or $1,200 per TCM in 2008 dollars). As new technology is developed, costs for desalination and recycled wastewater may decrease, making them more economically competitive with traditional supplies. If desalination costs were to be similar to or less than those for wastewater recycling, increased use of desalination (when possible) would be expected, along with reduced wastewater recycling, because users will prefer the less expensive supply. For wastewater recycling, the major costs come from adding capacity at the wastewater treatment plant and expanding the current water-redistribution system. Household and industrial water conservation is available at a variable cost represented by a constant-elasticity-of-demand curve for residential users, and survey-based cost functions for industrial users (Jenkins and others 2003). Traditional water supplies from surface water and groundwater incur operating costs for pumping, recharge, and water treatment, and some relatively saline urban supplies also incur additional user costs because of poor water quality (Jenkins and others 2001).

Although it is quite comprehensive, CALVIN—like all models—has limitations. CALVIN has fixed monthly urban and agricultural economic water demands (based on "normal" water year demands), water use efficiencies, and environmental requirements. Urban and agricultural demands, water use efficiencies, and environmental requirements can vary by month, but do not vary by year or year type. CALVIN does not include minimum instream flow requirements for temperature or water-quality control purposes. Hydropower representation is limited to a few major facilities. Reservoir and river recreation values are not included. Groundwater basins are highly simplified; stream–aquifer interactions and deep percolation because of rainfall are not modeled in CALVIN, but rather controlled by fixed inflows based on the Central Valley Groundwater Simulation Model No Action Alternative (CVGSM NAA) data (Jenkins and others 2001). Some significant uncertainties also exist regarding inflows and return flows in some parts of the system, primarily in the Tulare Basin.

In addition, the model's assumption that water managers have perfect foresight about hydrological conditions somewhat reduces scarcity and its associated costs during droughts (Draper 2001). Draper (2001) found that the benefits of expanding storage can be two to five times greater with limited foresight optimization than with perfect foresight optimization. The CALVIN model represents an ideal water market (i.e., no transaction costs, risks, or uncertainty), where transfers are only limited by physical infrastructure capacities, environmental flow requirements, and the economic value of water. Water rights, as defined today, have been replaced by a market-driven allocation system, where water is supplied to users to maximize the economic benefit of the state as a whole. Perfect foresight and a lack of institutional barriers allow water users to make optimal plans for water transfers, whereas in practice some of these transfers may not occur. These assumptions lead to idealized results, which can be interpreted to represent the minimum (or lower bound) costs that can be obtained from more flexible operations. Nevertheless, despite these and other documented limitations (Jenkins and others 2001), CALVIN is the most comprehensive tool available to assess management possibilities for California's water-supply system, and has provided insights for various water-management actions.

Modeling Regulatory Alternatives

The two strategies modeled in this study have the same infrastructure, water demands, and non-Delta environmental water demands. They differ in the amounts of water that may be exported through the Delta pumps, and the volumes of water that must flow to the ocean (net Delta outflow). Shown in Table 1 are the various modeling runs that reflect the two distinct strategies: reducing Delta pumping, and increasing MNDO. The corresponding Delta pumping and required Delta outflow is shown for each alternative.

Restricting Delta Exports

In this strategy, exports are restricted by modifying the pumping plant capacities for the State Water Project (Banks), Central Valley Project (Jones), and the Contra Costa Water District (Rock Slough, Old River, and Contra Costa). Relative to the base case—which corresponds to Delta regulatory conditions preceding the 2007 federal court decision to protect delta smelt, but with projected 2050 water demands—the model was run for successive levels of export restrictions: decreasing all pumping plant capacities by 50% and 75%, and setting all pump capacities to zero (i.e., no exports).[2] Diversions for in-Delta agriculture and the North Bay Aqueduct are allowed to continue because the intent of this modeling alternative is to assess the impacts of reduced exports from the southern Delta pumps. The reduction or abandonment of exports examined here is not the sudden unavailability of water exports resulting from levee collapse (Illingworth and others 2005) or other catastrophic events, but a planned and prepared cutback, where water users have time to develop conservation programs and add other cost-effective supply sources.

For all restricted Delta export runs, Delta outflow requirements are kept at current (pre-Wanger Decision) levels, corresponding approximately to the regulations in D–1641, the water rights decision accompanying the most recent water quality control plan for the Delta.[3] The MNDO range from 221 million cubic meters (MCM) per month in September to 461 MCM per month in March. The annual MNDO ranges from 4.6 billion cubic meters (BCM) per year to 10.2 BCM per year, with an average value of 6.9 BCM per year.

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[2] For Banks, the 50% and 75% reductions are relative to the pumping plant's hydraulic capacity of 241 $m^3 s^{-1}$.

[3] In CALVIN these outflow requirements are derived from DWRSIM_220D09B-Calfed-514-output (DWR 1998; Jenkins and others 2001).

Increasing Delta Outflow Requirements

For this set of runs, required Delta outflows are systematically increased from current levels by raising the MNDO values.[4] For example, if the new monthly MNDO is 308 MCM per month, all months with required flows below this value are raised to 308 MCM, and months with higher required outflows are unchanged. For the three levels above 1,974 MCM month, the minimum outflow requirement is an average over all months because there is not always enough water in the system to meet the minimum monthly standard. In these dry months, the minimum flow is at least 1,974 MCM. For example, in the scenario with 2,738 MCM per month requirements, the flow in some months might be as low as 1,974 MCM, but the overall monthly average is 2,738 MCM. At this level of required outflow, there is, on average, very little water available for diversions from the Delta: 94% of all modeled unimpaired inflows in the Delta watershed must be sent to the ocean.

RESTRICTING DELTA EXPORTS RESULTS AND DISCUSSION

Delta Exports and Outflows

Restricting Delta exports below those of the base case, results in less annual average exports. The

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4 For the increasing Delta outflow requirement pumping plant capacity at all southern Delta facilities were set to their regulatory limit, except Banks pumping plant. Capacity at Banks was set to the proposed SDIP capacity of 241 $m^3 s^{-1}$ (8,500 cfs).

Table 1 Modeled runs and strategies

Modeled alternative	**Banks and total Delta pumping capacity**[a]		**Required Delta outflow**[b]	
	($m^3 s^{-1}$)	**(MCM per month)**	**Minimum (MCM per month)**	**Annual average (MCM per year)**
Restricting Delta exports				
No export (NE)	0/0	0/0	221	6,899
Restricted transfers (RT)	0/0	0/0		
75% capacity reduction (75%R)	60 / 97	159 / 255		
50% capacity reduction (50%R)	120 / 194	317 / 511		
Base conditions (BC)[c]	187 / 334	491 / 878		
Increasing minimum net Delta outflow				
Base conditions[d] ($m^3 s^{-1}$)	241 / 388	633 / 1,020	221	6,899
308 MNDO[e]			308	7,030
617 MNDO			617	8,986
863 MNDO			863	11,262
1,233 MNDO			1,233	15,136
1,480 MNDO			1,480	17,885
1,727 MNDO			1,727	20,757
1,850 MNDO			1,850	22,219
1,974 MNDO			1,974	23,689
2,355 MNDO			1,974	28,260
2,546 MNDO			1,974	30,546
2,736 MNDO			1,974	32,827

[a] Banks and total Delta pumping capacity are presented in cubic meters per second ($m^3 s^{-1}$) and as the monthly average pumping equivalents in million cubic meters per month. For example, with a 75% reduction, the pumping capacity for Banks is 60 $m^3 s^{-1}$ (the monthly average equivalent is 159 MCM per month) and total Delta pumping is 97 $m^3 s^{-1}$ (the monthly average equivalent is 255 MCM per month).

[b] Monthly minimums vary by month and water year type in the current regulatory framework; 221 MCM is the lowest monthly level.

[c] Base conditions with 2050 water demands and Banks pumping plant at regulatory capacity (varies by month).

[d] Base conditions with 2050 water demands and Banks pumping plant at hydraulic capacity (241 $m^3 s^{-1}$).

[e] MNDO is minimum net Delta outflow indicated in metric units, million cubic meters (MCM).

export volumes also become less variable: for 50% and 75% reductions in capacity, pumping was at or near the remaining capacity in all months and years. Pumping capacity is not always fully utilized under base conditions, so the decline in exports is somewhat less than proportional; relative to base case average exports of about 7.3 BCM per year, the 50% and 75% reductions in pumping capacity lead to 6.0 BCM and 3.1 BCM of annual exports (declines of 18% and 58%), respectively. Base case exports are slightly more than recent (pre-Wanger Decision) exports because of higher overall water demands for 2050 projected population and land use.[5] Thus, although the details of the restrictions are somewhat different, these two restricted export alternatives provide a broad indication of the potential long-term effects of the Wanger Decision, which is estimated to reduce SWP exports by 22% to 30% on average (DWR 2011).

Although these scenarios maintain current required outflows, export restrictions increase water flowing to the ocean by increasing the "surplus" outflows (flows exceeding the requirement). There is approximately 9.5 BCM per year of surplus Delta outflow under the baseline condition, which increased by 6.7 BCM per year when exports were prohibited. The total outflow from the Delta increased from 16.4 BCM per year to 23.1 BCM per year, with most of the increase occurring in winter. Only minor changes in summer Delta outflows were observed.

Shortages and Costs

When exports are restricted, water shortage or "scarcity" rises, as do scarcity costs and operating costs. "Scarcity costs" are the economic costs to local water users of these shortages; including lost agricultural profits and costs to households and businesses of water conservation measures and other reductions in water use. Operating costs—the annual cost of delivering usable water—also can increase if more costly water sources are used. Statewide net costs (operating costs plus scarcity costs minus hydropower benefits) for each management strategy of varying Delta exports are presented in Figure 3. As Delta exports are reduced by 50% and 75%, net operating costs decrease because of decreased costs for Delta pumping and subsequent aqueduct pumping. Urban scarcity is minimal, because such operating costs dominate the total cost of urban scarcity and operating costs. In contrast, agricultural scarcity increases significantly as exports are reduced, and therefore even as operating costs decrease, net costs of agricultural scarcity and operating costs increase.

Annual statewide net costs of the water system rise from $2.7 billion to $4.1 billion per year when moving from base conditions to a situation without exports;

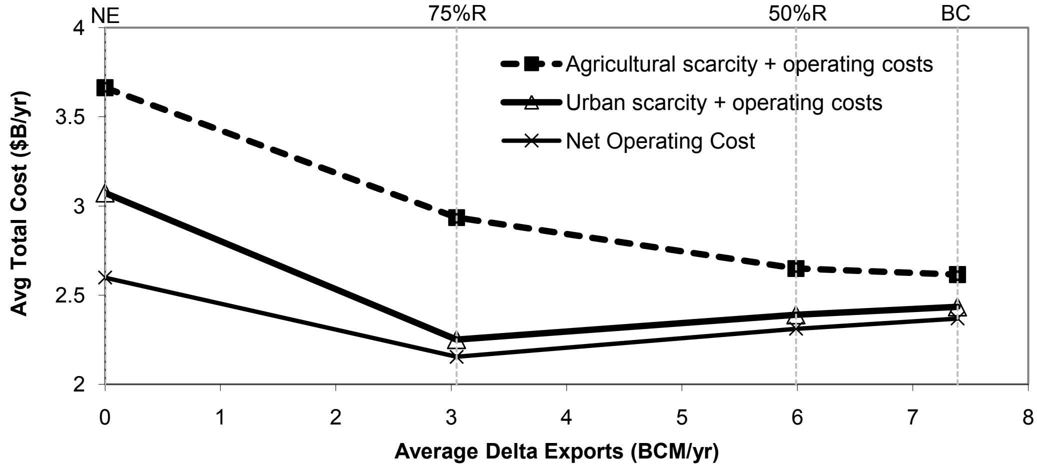

Figure 3 Annual average net statewide costs with changing export restrictions

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[5] See Lund and others (2007), Table 6.1 for exports in the 1995–2005 period by region and sector. Total Delta exports (excluding in-Delta diversions) averaged 6.9 BCM over this period.

a net increase of $1.5 billion per year (Table 2). Operating costs (including desalination, water treatment, recycling, and pumping) rise with export restrictions, moving from $2.4 billion per year under base conditions to $2.6 billion per year without exports (Table 2). These increases are driven by the use of more costly supply alternatives, such as desalination and wastewater reuse, and reduced hydropower production.

Overall, most cost increases come from increased scarcity costs. Even under base conditions, there is some scarcity—just below 3.7 BCM per year—because availability, conveyance and infrastructure capacity, and the cost of additional supplies prohibits some users from obtaining all the water they could economically put to use (Table 3). Agricultural users bear the brunt of additional export restrictions, while urban scarcity and scarcity costs remain relatively constant until exports are severely limited. The higher willingness to pay for water in the urban sector accounts for this disparity: as exports are restricted, agricultural users who are in a position to transfer water to the urban sector do so profitably. With restrictions at the pumps, the sales come from agricultural users in the San Joaquin and Tulare basins. The combination of reduced exports and transfers means that agriculture in this part of the state faces significant scarcity. When exports are ended altogether, an estimated 0.49 million hectares go out of production (Tanaka and others 2008). Meanwhile, Sacramento Valley farmers are essentially cut off from the water market, and therefore experience a small increase in water availability. Southern California farmers, who depend on Colorado River flows, are also unaffected because the Colorado River Aqueduct has no additional capacity to transfer water to urban users. Without Delta exports, the greatest urban impacts are in Southern California, which experiences additional shortages on the order of 321 MCM per year. In the Bay Area, the hardest hit agencies are those that contract with the SWP and CVP in Santa Clara and Alameda counties (36 MCM per year).

If agricultural users in the San Joaquin and Tulare basins do not transfer water to Southern California (and other users on the west side of the San Joaquin and Tulare basins), annual average agricultural scarcity decreases by 1.2 BCM per year to 8.1 BCM per year. Urban scarcity increases by 137 MCM per year to 566 MCM per year. Average annual scarcity costs to agricultural users decrease by $146 million per year, but urban scarcity costs increase by $180 million per year. Most increased urban scarcity costs occur in Southern California ($142 million per year) and Bakersfield and Delano in the Tulare Basin ($34 million per year). Overall, statewide operating costs increase from $4.1 billion per year to $4.8 bil-

Table 2 Annual average statewide operating costs with export restrictions

	Statewide annual average costs ($ M / year)				
	RT	**NE**	**75%R**	**50%R**	**BC**
Groundwater	771	736	773	806	818
Surface water treatment	1,143	1492	2,044	2,060	2061
Desalination	1,933	541	55	55	55
Recycled water	1,446	1,452	354	348	347
Surface water pumping	449	981	1,669	1,784	1,832
Hydropower benefits	2,476	2,605	2,746	2,745	2,749
Total net operating costs[a]	3,266	2,596	2,151	2,308	2,365
Statewide scarcity cost	1,573	1,540	877	416	312
Total statewide net costs[a]	4,839	4,136	3,028	2,724	2,677

[a] Totals may not sum because of rounding. RT is no exports with restricted transfers, NE is no exports, 75%R is 75% reduction in export pumping capacity, 50%R is 50% reduction in export pumping capacity, and BC is base case (2050 demands).

Table 3 Agricultural and urban scarcity and scarcity costs with export restrictions

	Average scarcity (MCM per year)					Average scarcity cost ($M per year)				
Region	**RT**	**NE**	**75%R**	**50%R**	**BC**	**RT**	**NE**	**75%R**	**50%R**	**BC**
Agricultural economic water users										
Sacramento Valley	169	169	185	363	391	2	2	2	4	4
San Joaquin Valley	2398	2302	2299	1404	745	164	153	153	50	15
Tulare Basin	4415	5759	4486	2040	1238	563	719	435	93	37
Southern California	1161	1151	1161	1161	1161	191	191	191	191	191
Statewide[a]	8142	9392	8131	4968	3536	919	1065	781	338	247
Urban economic water users										
Sacramento Valley	0	0	0	0	0	0	0	0	0	0
San Joaquin Valley	36	36	0	0	0	51	51	0	0	0
Tulare Basin	42	0	0	0	0	37	0	0	0	0
Southern California	488	392	115	94	74	566	424	97	78	66
Statewide[a]	459	428	115	94	74	654	475	97	78	66
Total of all economic water users[a]										
Sacramento Valley	169	169	185	294	317	2	2	2	4	4
San Joaquin Valley	2434	2339	2299	1138	604	215	204	153	50	15
Tulare Basin	4457	5759	4486	1654	1004	600	719	435	93	37
Southern California	1649	1554	1277	1017	1001	757	615	288	270	257
Statewide[a]	8708	9820	8246	5062	3609	1573	1540	877	416	312

a Totals may not sum because of rounding. RT is no exports with restricted transfers, NE is no exports, 75%R is 75% reduction in export pumping capacity, 50%R is 50% reduction in export pumping capacity, and BC is base case (2050 demands).

lion per year. The large net increases in operating costs result from increased use of desalination, reduced hydropower generation, and reductions in surface water pumping and treatment costs. Overall, there is an additional $700 million per year of scarcity and operating costs when agricultural water transfers from the San Joaquin and Tulare basins are prohibited.

Shifting Supply Portfolios

Export restrictions lead to some significant adjustments in the state's water supply portfolio. Scarcity is a big part of the adjustment for agricultural users who also have financial incentives to fallow land and make more efficient use of remaining supplies. For the urban sector, water transfers (mainly from agriculture) become an important part of the supply portfolio. For both agricultural and urban areas, groundwater storage also becomes more important. Finally, as traditional supplies of freshwater become more costly or unavailable, urban areas use recycled wastewater and desalination to stretch existing supplies.

Recycled water is assumed to be available at a cost of $811 per TCM (in 1995 dollars, equivalent to $1,200 in 2008 dollars). Base case operations include approximately 269 MCM per year of wastewater reuse statewide; this increased to 1,199 MCM per year on average when exports were eliminated. Without Delta exports, southern California communities rely on wastewater recycling for 10.1% of their demand (approximately 1,036 MCM per year), versus 3.5% of demand (128 MCM per year) in the South Bay and southern Central Valley, and 1.8% of demand (35 MCM per year) north of the Delta.

Ocean desalination, which at $1,135 (in 1995 dollars, equivalent to $1,680 in 2008 dollars) per TCM is considerably more expensive than recycled water, expands in a more limited way. In the model, only eight urban areas have access to unlimited ocean desalination, and only three urban areas use this source under base case regulatory conditions (Santa Barbara–San Luis Obispo, San Diego, and the eastern zone of the Metropolitan Water District of Southern California). When Delta exports are eliminated, two more urban areas join this group (San Francisco and the Santa Clara Valley). Urban areas will only use desalination when all less expensive supplies have been exhausted. For all urban areas, except Santa Barbara–San Luis Obispo (included in the Tulare region) and the Santa Clara Valley, desalination use is sporadic (less than 15% of the time). These results may overstate the extent to which desalination is actually used, because CALVIN makes desalination more attractive than it may be in practice.[6] However, some agencies may choose to invest in desalination as a hedge against drought risk, and CALVIN underestimates this type of risk-averse investment strategy.

Figure 4 provides an overview of the shifting water supply portfolio for California. Under base conditions, users both north and south of the Delta rely on surface water for over half of their demands. After surface water, groundwater is the most commonly used source. When exports are eliminated, users north of the Delta increase their use of all sources by a small amount (1% to 2%) to reduce their use of more expensive treatment options (i.e., wastewater recycling) and to reduce annual average scarcity. Users south of the Delta are forced to reduce their use of surface water by nearly a quarter (14% of total use), and their groundwater pumping by roughly one-sixth (5% of total use). To reduce scarcity, the volume of wastewater recycling and desalination more than quadruples. (Re-use here is within-region agricultural reuse of agricultural drainage.) Overall water use declines by 18% south of the Delta.[7]

Environmental Water Costs

Restricting exports generally increases the opportunity costs of furnishing water for environmental uses. CALVIN includes two types of environmental water uses: minimum instream flows and fixed deliveries for environmental purposes (e.g., wildlife refuges). Both are treated as fixed regulatory requirements. In the base case, an additional thousand cubic meters of water for the environment costs other water users anywhere from under a dollar to more than $1,135 per TCM (Table 4). These "marginal" costs are highest when the environmental flows are "consumptively used" (i.e., when the water cannot be reused downstream), such as the Mono Lake and Owens Lake inflows, and flows for wildlife refuges.

Restricting Delta exports slightly decreases the marginal costs of environmental flows north of the Delta, while greatly increasing these costs south of the Delta (Table 4). The greatest increases in marginal costs of environmental flows are for the required flows into Mono and Owens lakes, and the Kern and San Joaquin wildlife refuges. Decreasing exports also reduces the costs of meeting Delta outflow requirements.

The Value of New Facilities

The statewide economic value of new conveyance or storage capacity is estimated as the value of an additional thousand cubic meters of capacity ("marginal value"). Tighter export restrictions typically increase the value of expanding key conveyance facilities more than expanding surface reservoirs (Table 5).

Conveyance Facilities

With restricted Delta exports, facilities including the Hayward Intertie, the Hetch–Hetchy Aqueduct, Mokelumne Aqueduct, Colorado River Aqueduct, and the proposed New Don Pedro Intertie could provide additional benefits if expanded. These facilities would

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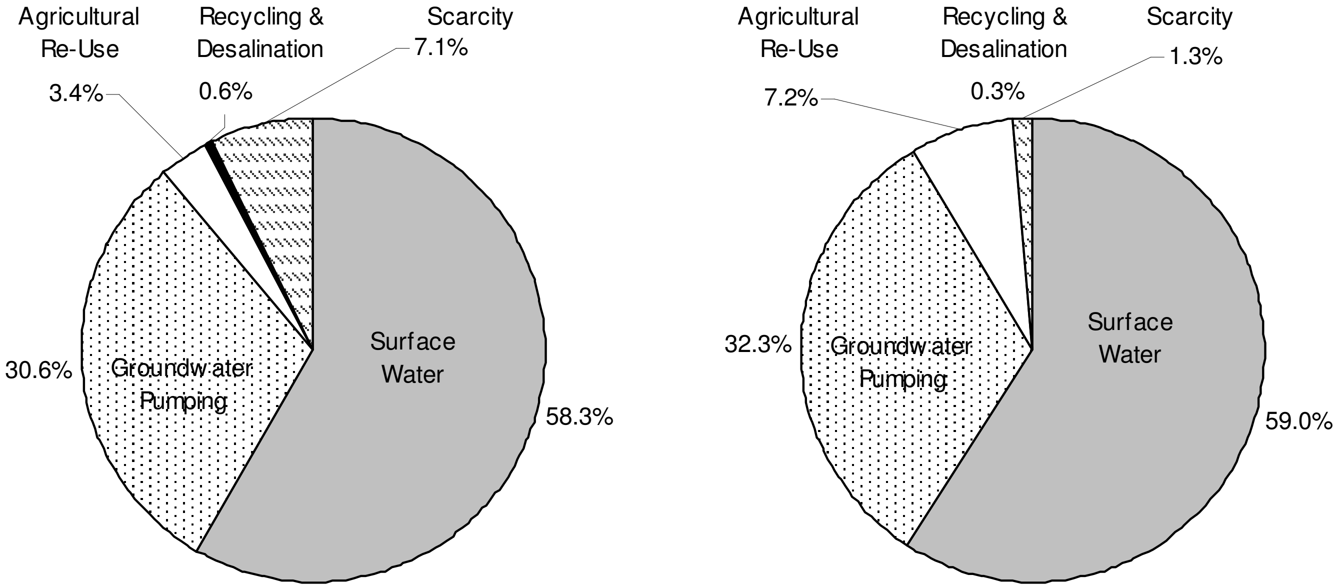
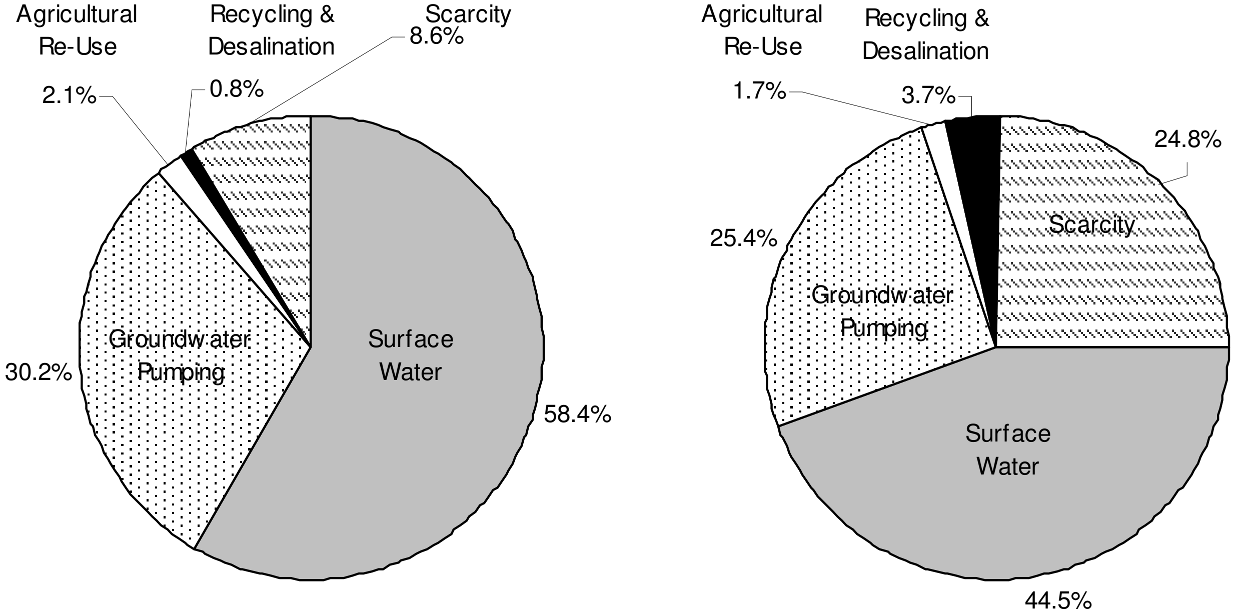
[6] In CALVIN, coastal urban areas have unlimited access to desalination plants without having to invest in construction (capital) costs or pay maintenance costs for existing facilities. They can call upon desalination for infrequent, but large volumes of water at the same cost as if they used it frequently for small volumes. For example, San Francisco only uses desalination for 3 months out of the 72 years, but uses about 17 MCM per month each time. In practice, it would not be economically feasible to build a 17 MCM per month (6.7 $m^3 s^{-1}$) desalination plant to be used only three times in 72 years.

[7] Measured as the result of increased scarcity, which increases from 8.6% to 24.8% of the portfolio (percent change of water used).



North of Delta –Base Case

North of Delta – No Exports



South of Delta – Base Case

South of Delta – No Exports

Figure 4 Water portfolio north and south of the Delta, with and without exports (2050)

Table 4 Marginal cost of environmental water requirements with changing export restrictions

Region (North or South of Delta)	Location	NE	75%R	50%R	BC
		Average marginal economic cost ($ per TCM)			
	Minimum instream flow				
North	Trinity River [a,b]	38.1	39.1	41.1	41.8
North	Sacramento River	1.9	1.9	2.4	2.5
North	Clear Creek	19.5	19.5	19.9	19.9
North	Feather River	0.6	0.5	0.3	0.4
North	Yuba River	0.4	0.4	0.4	0.5
North	American River	1.0	0.7	0.6	0.7
North	Mokelumne River	6.6	4.5	4.5	4.6
North	Calaveras River	0.0	0.0	0.0	0.0
South	San Joaquin River	225.0	169.8	87.8	43.9
South	Stanislaus River	3.2	3.2	2.7	2.7
South	Tuolumne River	3.2	3.2	2.7	2.8
South	Merced River	49.0	48.9	43.9	24.1
	Refuges				
North	Sacramento east refuges[a]	1.1	1.8	3.2	3.5
North	Sacramento west refuges[a]	0.5	1.3	2.7	3.2
South	Pixley National Wildlife Refuge[a]	136.8	136.7	79.0	41.0
South	Kern National Wildlife Refuge[a]	613.3	206.2	92.2	46.0
South	San Joaquin Wildlife Refuge[a]	487.5	187.6	73.5	28.9
	Other				
North	Required Net Delta Outflow	0.3	1.2	2.6	3.1
South	Delta Mendota Pool	106.4	106.3	66.7	25.7
South	Owens Lake[b]	1411.8	1055.6	934.8	893.2
South	Mono Lake[b]	1706.3	1326.9	1198.2	1154.2

a Consumptive environmental flows.
b Marginal values of environmental flows immediately downstream of hydropower-generating reservoirs may also reflect lost benefits of hydropower generations.

allow urban areas in the Bay Area and Southern California to access more water, which becomes increasingly scarce without Delta exports. Facilities that provide water to the Bay Area are especially valuable. Although the Bay Area and Southern California have similar levels of reliance on supplies from the Delta (around a third), historically, southern California has benefited from earlier investments in interties, largely through its large regional wholesaler, the Metropolitan Water District of Southern California. In contrast, the Coastal Aqueduct becomes less valuable as Delta exports are restricted, because it depends entirely on water from the California Aqueduct and is without an alternative water source. Unsurprisingly, as Delta export capacity is reduced, the value of restoring export capacity at the pumping plants also increases.

Expanding Surface and Underground Storage

Statewide, the volume of water stored in existing surface reservoirs is higher without exports (Figure 5). North of the Delta storage is significantly higher because these reservoirs can no longer serve locations south of the Delta.[8] South of the Delta, overall storage levels tend to be higher without exports, but

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[8] Higher reservoir storage levels also generate more hydropower, which is modeled as a benefit to the system.

Table 5 Marginal values of expanding capacity at key facilities with changing export restrictions

Region (North or South of Delta)	Name of facility	Average marginal value of expansion ($ per TCM per year) NE	75%R	50%R	BC
	Conveyance facilities ($ per TCM per year)				
North	Freeport Project	6	0	0	0
North	Mokelumne River Aqueduct	222	0	0	0
South	New Don Pedro Intertie[a]	700	375	347	204
South	Hetch Hetchy Aqueduct	1107	556	433	389
South	EBMUD—CCWD Intertie	17	0	0	0
South	Hayward Intertie	621	300	174	131
South	Jones Pumping Plant	1524	161	45	0
South	Banks Pumping Plant	1528	165	49	2
South	Cross Valley Canal	182	2	1	1
South	Friant-Kern Canal	6	4	1	0
South	Coastal Aqueduct	0	951	1064	1111
South	Colorado River Aqueduct	820	458	336	293
	Surface reservoirs ($ per TCM per year)				
North	Shasta Lake	6	6	6	6
North	Clair Engle Lake	2	2	2	2
North	Black Butte Lake	4	5	6	6
North	Lake Oroville	10	11	11	12
North	Thermalito Afterbay	3	5	6	7
North	New Bullards Bar Reservoir	14	14	14	15
North	Englebright Lake	36	36	36	36
North	Clear Lake & Indian Valley Reservoir	0	1	2	2
North	Camp Far West Reservoir	2	3	4	5
North	Folsom Lake	8	9	10	11
South	New Melones Reservoir	7	7	7	7
South	San Luis Reservoir	0	0	0	0
South	New Don Pedro Reservoir	14	14	14	15
South	Hetch-Hetchy Reservoir	4	4	4	4
South	Millerton Lake	24	14	7	5
South	Lake Kaweah	135	134	77	41
South	Lake Success	120	120	69	37
South	Lake Skinner	22	260	381	423
	Artificial recharge facilities ($ per TCM per year)				
South	Santa Clara Valley	1518	193	69	25
South	Mojave	289	310	319	318
South	Antelope Valley	1390	1009	899	852

a Hypothetical expansion from zero capacity.

individual reservoir storages vary. Consequently, the value of additional reservoir capacity at many locations decreases as export restrictions are tightened. Northern California reservoirs all lose value because they are less useful for meeting statewide water demands. Some storage south of the Delta loses value because less water is available to store (Table 5). Reservoirs that would benefit from expansion tend to be in the Tulare Basin, where water can be exported to urban areas of Southern California. These reservoirs are generally already at capacity in winter. If expanded, they could store more winter flows for use in summer.

Statewide, active groundwater storage is generally higher without exports, for similar reasons (Figure 5). Some artificial recharge facilities in areas dependent on Delta exports become more attractive when exports are restricted (Table 5). The Santa Clara Valley would benefit from recharging more treated wastewater, as would agencies in the Antelope Valley and the Mojave Basin. Urban areas also could benefit somewhat from diverting more fresh water into their aquifers for storage, when capacity is available.

Summary

Increasing export restrictions has significant consequences for deliveries and costs for users south of the Delta. The effects are felt most quickly in the agricultural sector in the San Joaquin Valley and Tulare Basin, where even an 18% cut in total export volumes entails significant scarcity costs (about $90 million per year). As exports are further restricted, costs increase dramatically for all users. Urban agencies in the Bay Area and Southern California, which also depend on the Delta, can make up much of the initial loss through water transfers and other adjustments. New facilities, such as the Freeport Project and interties to the California Aqueduct, allow urban users to replace in-Delta water with other sources. Consumptive environmental requirements have high costs, especially for refuge and wildlife areas located south of the Delta. Without exports, outflows from the Delta increased to 23.1 BCM per year, with most of the increase occurring in winter. Overall, reducing or eliminating Delta exports would be costly for all sectors.

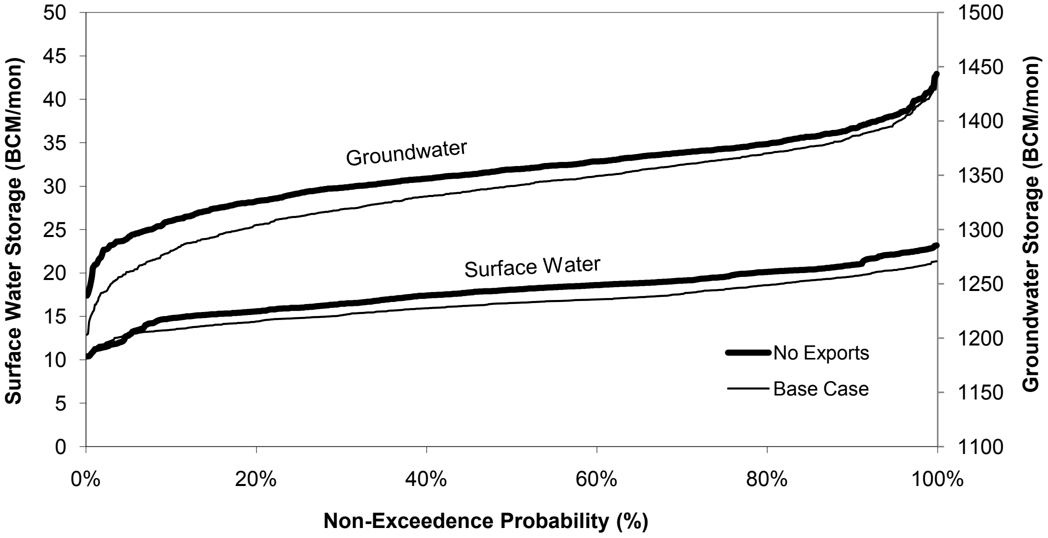


Figure 5 Statewide surface water and groundwater storage with changing export restrictions. Non-exceedence probability is the probability of having storage volumes below (not exceeding) the given storage volume. For example, in the No Exports case for surface water, there is a 20% monthly chance that surface water storage will be less than approximately 15 BCM.

INCREASING DELTA OUTFLOW REQUIREMENTS RESULTS AND DISCUSSION

Delta Outflows and Exports

Increases in MNDO requirements decrease surplus outflows and require reductions in other consumptive uses both inside and outside of the Delta. Under base conditions (221 MCM per month or 6,899 MCM per year), surplus outflows (any volume of outflow greater than required outflow) occur in all months (on average), but when the MNDO is raised to 1,974 MCM per month, surplus flows only remain from November through June and at lower volumes. When the MNDO increases to an average of 2,738 MCM per month, surplus outflows are eliminated altogether. The highest total outflows (required plus surplus) always occur in winter (December through March) and the lowest outflows in summer (June through September), which is the inverse of the demand patterns for agricultural and urban users.

As outflow requirements increase, average annual deliveries to agricultural users from both Delta exports and upstream surface water supplies (upstream diversions) decreased (Figure 6). The effect on agricultural deliveries is orders of magnitude greater than for urban users. Upstream diversions that serve urban demands for Redding and Sacramento increase as required outflow increases (as shown with slightly negative values in Figure 6). As the outflow requirement increases, Redding pumps less groundwater and diverts more Sacramento River water to meet their demand. As expected, deliveries to urban users from Delta export supplies decrease as required outflows are raised (shadows the ”upstream diversions” line for agriculture in Figure 6). The one-to-one line on Figure 6 shows the flexibility in the system such that a unit of increased required outflow does not translate into a unit of decreased deliveries to agricultural or urban users. However, the steeper slope of the reduced deliveries to agriculture from Delta exports indicates a more direct relationship between increased required outflows and reduced Delta exports delivered to agriculture.

Scarcity and Costs

As MNDO increases, flows over the Tehachapi Mountains to Southern California are relatively unaffected until the minimum outflows exceed 1,974 MCM per month. Flows into Southern California drop from 2.7 BCM per year to less than 1.9 BCM per year when MNDO is increased to 2,736 MCM per month. As with the reduced export alternative, the reduction in available supplies from the Delta largely comprises transfers from the San Joaquin and Tulare basins. The

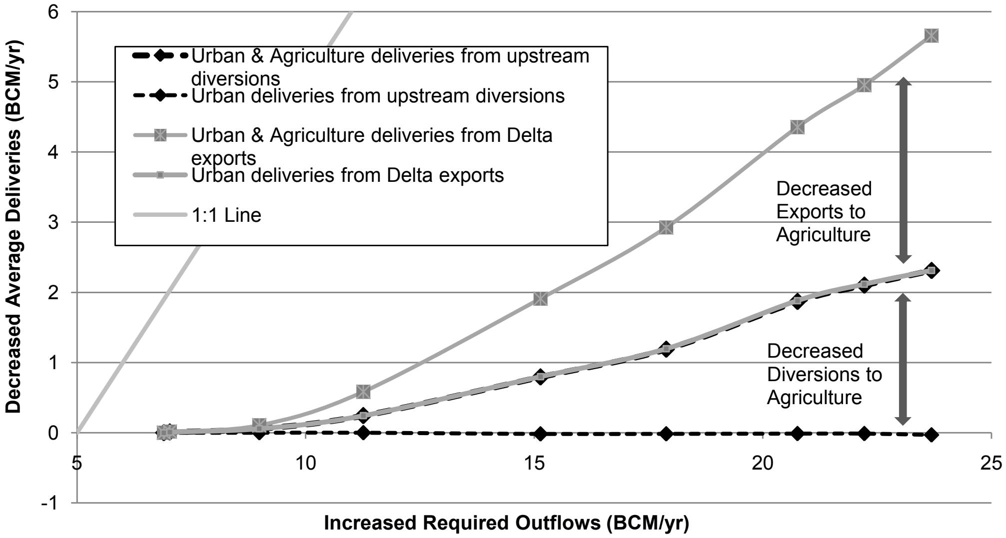


Figure 6 Annual average decrease in Delta exports and upstream diversions for agricultural and urban users with increasing MNDOs

Table 6 Scarcity and scarcity costs with increasing MNDOs

	Annual average scarcity (MCM per year)					**Annual average scarcity cost** ($ M per year)				
Region	**BC**	**1233**[b]	**1974**[b]	**2355**[b]	**2736**[b]	**BC**	**1233**[b]	**1974**[b]	**2355**[b]	**2736**[b]
Agricultural economic water users										
Sacramento Valley	391	2125	6297	7743	8367	4	53	380	530	599
San Joaquin Valley	745	1571	4276	5274	5446	14	48	316	434	454
Tulare Basin	1238	2205	3939	5584	7699	36	110	332	608	1057
Southern California	1161	1161	1161	1161	1161	191	191	191	191	191
Statewide[a]	3536	7064	15673	19762	22674	245	402	1219	1764	2301
Urban economic water users										
Sacramento Valley	0	0	4	5	6	0	0	0	0	0
San Joaquin Valley	0	0	11	11	17	0	0	4	5	6
Tulare Basin	0	0	0	0	0	0	0	16	16	20
Southern California	74	94	109	115	270	0	0	0	0	0
Statewide[a]	74	94	125	131	294	0	0	20	21	26
Total of all economic water users[a]										
Sacramento Valley	391	2125	6301	7749	8373	4	53	380	530	599
San Joaquin Valley	745	1571	4288	5285	5464	14	48	319	439	460
Tulare Basin	1238	2205	3939	5584	7699	36	110	348	624	1076
Southern California	1235	1254	1270	1275	1431	191	191	191	191	191
Statewide[a]	3609	7158	15797	19894	22969	245	402	1239	1785	2327

a Totals may not sum because of rounding.
b Minimum net Delta outflow (MNDO) (MCM per month).

ability to purchase lower-value water from agricultural users means urban water users south of the Delta avoid supply reductions until outflows are restricted at the highest levels.

In contrast, agricultural regions face additional shortages almost as soon as the MNDO exceeds base conditions (Table 6). However, these increases are usually modest until the MNDO reaches about 1,233 MCM per month (or 15.2 BCM per year—more than double current annual levels), but then rise steadily. By the time the average MNDO reaches 2,736 MCM per month, scarcity and scarcity costs are higher in all agricultural regions, except those in Southern California, which rely on Colorado River water and cannot transfer additional supplies to urban users because of capacity limitations.

Agricultural water users who compete directly with urban users or required environmental flows have the largest increases in scarcity. Unlike the export restriction scenarios, the Sacramento Valley and San Joaquin River and eastside San Joaquin agricultural users are not immune to changes in Delta outflow requirements. As the MNDO increases, consumptive use in both the Sacramento and San Joaquin river systems decreases, allowing more water to reach the Delta. At the highest level of required outflow, an additional 3.8 BCM per year flows in the Sacramento River below Rio Vista, and an additional 5.6 BCM per year flows in the San Joaquin River at Vernalis.

As scarcity increases, so do scarcity costs (Table 6 and Figure 7). Operating costs also rise, driven by the use of more costly supply alternatives and reduced hydropower production. Overall net statewide costs increase from $2.6 billion per year to $4.9 billion per year when outflow requirements are increased to 2,736 MCM per month (Table 7).

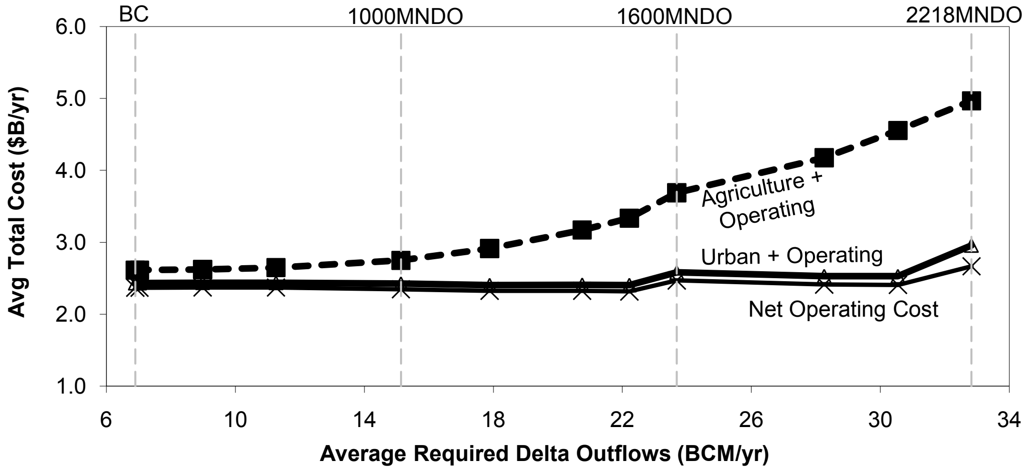


Figure 7 Annual average net statewide costs with increasing minimum net Delta outflows

Table 7 Annual average statewide net operating costs with increasing minimum net Delta outflows

	Annual average cost ($M per year)				
	Base	**1,233**[b]	**1,974**[b]	**2,355**[b]	**2,736**[b]
Groundwater	818	792	755	727	698
Surface water treatment	2,060	2,066	2,059	2,057	1,669
Desalination	55	55	213	226	315
Recycled water	348	352	374	374	1,344
Surface water pumping	1,834	1804	1,743	1,698	1,159
Hydropower benefits	2,751	2,720	2,675	2,650	2,637
Total net operating costs[a]	2,364	2,349	2,470	2,433	2,548
Statewide scarcity cost	245	402	1,239	1,785	2,327
Total statewide net costs[a]	2,609	2,751	3,709	4,217	4,875

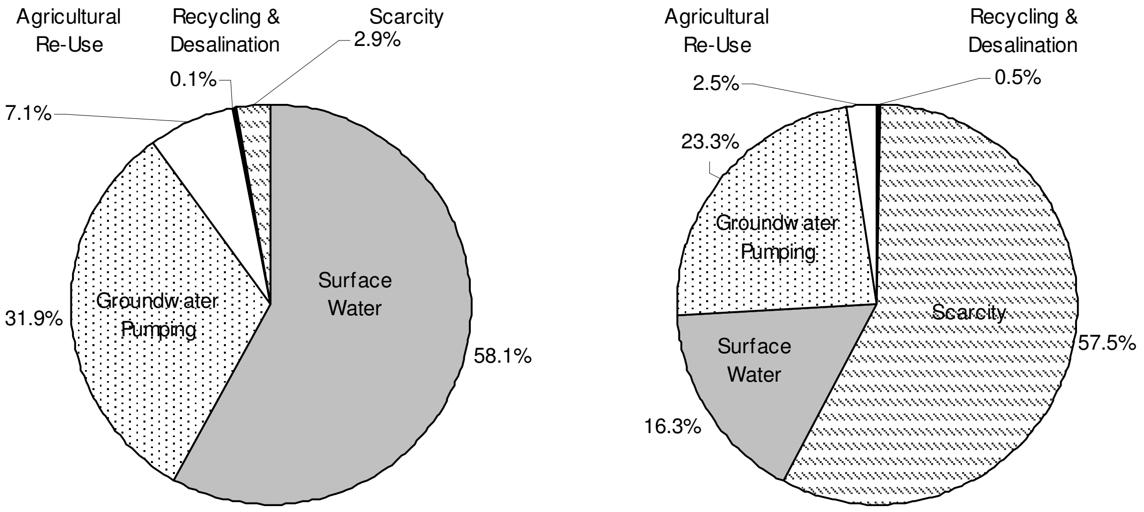
a Totals may not sum due to rounding.
b Minimum net Delta outflows (MNDO) (MCM per month).

Shifting Supply Portfolios

As with export restrictions, water users are forced to make adjustments to their overall supply portfolios. However, in this case users both north and south of the Delta are affected. The shifting composition of supply for these two regions is shown in Figure 8, which compares the base case for 2050 with a level of Delta outflow requirements comparable to the No Export alternative (1,909 MNDO). In this scenario—corresponding to 81% of modeled unimpaired flows in the Delta watershed—users both north and south of the Delta have substantial reductions in both surface water and groundwater deliveries and higher scarcity. The declines are most dramatic for users north of the Delta, whose surface supplies decrease 72% (from 58.1% to 16.3% of total supply), and whose overall water use declines by more than 55%. Users south of the Delta lose 30% of their surface supplies (18% of total use) and one-quarter of water deliveries overall.

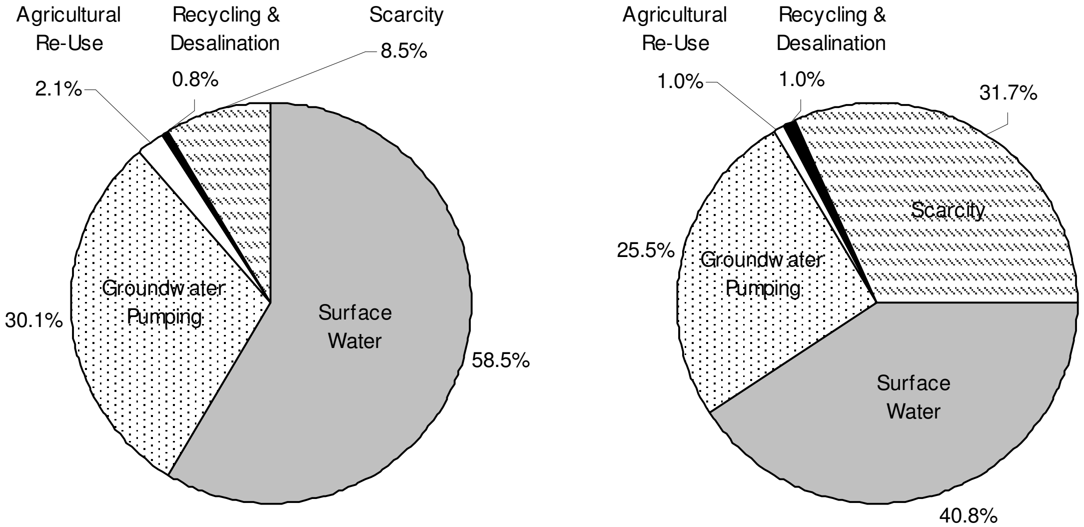
Recycled urban wastewater and desalinated water use increases as urban agencies make up the loss of lower-cost supplies from increasing MNDO requirements. Recycled water is used by urban demands across the state, with the most dramatic increase in southern California, from 202 to 989 MCM per year, when the MNDO increases from 2,546 to 2,736 MCM per month, respectively. Otherwise, increases in the Sacramento Valley, San Joaquin, Bay Area, and Tulare region (combined) are moderate, as the MNDO increases from the base case to 2,736 MCM per month, with ranges of 10 to 53 MCM per year and 80 to 96 MCM per year, respectively.

As with reduced exports, recycled water is used more than desalination. At a MNDO level of 1,974 MCM



North of Delta – Base Case

North of Delta – 2355 MNDO



South of Delta – Base Case

South of Delta – No Exports

Figure 8 Water portfolio north and south of the Delta with current and significantly increased net Delta outflows (2050) per month, the southern California, San Joaquin, Bay Area, and Tulare regions all increase their desalination, with the greatest amount occurring in the San Joaquin, Bay Area, and Tulare regions (130 MCM per year).

Environmental Water Costs

The marginal cost of environmental flows increases as deliveries are reduced to meet increasing Delta outflow requirements (Table 8). In contrast to the case of export restrictions, these added costs are shared more evenly across the state. As before, the marginal costs are highest for consumptively used environmental flows. In addition to the required Delta outflows themselves, the greatest increases in marginal costs are for the Trinity River minimum instream flows, Mono Lake and Owens Lake inflows, and the wildlife refuges.

The Value of New Facilities

Conveyance Facilities

As with restricted Delta exports, expansion of facilities that allow urban areas, primarily in the Bay Area and Southern California, to access more water have the highest economic benefit (Table 9). These

Table 8 Marginal opportunity cost of environmental water with increasing MNDOs

Region (North or South of Delta)	Location	Average marginal economic cost ($ per TCM)						
		Base	1,233[c]	1,480[c]	1,974[c]	2,355[c]	2,546[c]	2,736[c]
		Minimum instream flow						
North	Trinity River [a,b]	41.5	90.3	117.7	495.4	563.6	620.4	856.2
North	Sacramento River	2.4	5.5	7.2	40.7	40.9	39.9	45.3
North	Clear Creek	19.9	23.7	25.3	66.4	69.9	70.0	73.5
North	Feather River	0.5	2.8	3.5	6.5	7.3	7.4	11.7
North	Yuba River	0.5	0.6	0.6	0.9	0.7	0.7	0.9
North	American River	0.7	3.2	3.6	12.7	12.2	12.2	12.6
North	Mokelumne River	4.7	9.6	11.5	32.1	32.1	32.4	40.0
North	Calaveras River	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South	San Joaquin River	42.8	44.3	39.5	31.4	19.6	14.4	16.9
South	Stanisalus River	2.7	9.0	12.5	21.8	22.6	23.9	47.3
South	Tuolumne River	2.8	8.6	11.0	15.6	16.5	17.9	32.5
South	Merced River	23.9	17.3	14.1	12.2	10.3	10.9	17.0
		Refuges						
North	Sacramento east refuges[a]	3.5	42.2	64.2	352.0	408.4	458.2	652.2
North	Sacramento west refuges[a]	3.1	43.1	66.2	157.3	224.2	301.9	535.2
South	Pixley National Wildlife Refuge[a]	39.8	81.2	98.6	135.3	138.2	138.6	138.9
South	Kern National Wildlife Refuge[a]	44.8	92.7	118.0	182.1	235.1	293.5	509.7
South	San Joaquin Wildlife Refuge[a]	27.8	74.9	99.8	434.0	496.4	550.9	774.2
		Other						
North	Required Net Delta Outflow	2.9	46.8	71.8	407.1	471.0	526.6	752.7
South	Delta Mendota Pool	24.6	60.8	78.3	332.4	378.0	420.3	597.9
South	Owens Lake[b]	892.8	939.5	966.9	1028.7	1084.4	1145.9	1328.2
South	Mono Lake[b]	1153.8	1201.6	1230.3	1295.8	1354.7	1419.4	1611.4

a Consumptive environmental flows.

b Marginal values of environmental flows immediately downstream of hydropower-generating reservoirs may also reflect lost benefits of hydropower generation, in addition to downstream scarcity and operating costs.

c Minimum net Delta outflow (MNDO) (MCM per month).

Table 9 Average economic marginal values of expanded conveyance and storage facilities with increasing monthly MNDOs

Region (North or South of Delta)	Name of facility	Average marginal value of expansion ($ per TCM per year)					
		Base	1,233[a]	1,480[a]	1,974[a]	2,355[a]	2,546[a]
	Conveyance facilities ($ per TCM per year)[b]						
North	Freeport Project	0	3	25	25	25	32
North	Mokelumne River Aqueduct	0	1	2	2	2	2
South	New Don Pedro Intertie[c]	270	212	208	205	165	188
South	Hetch Hetchy Aqueduct	389	388	346	344	339	308
South	CCWD/EBMUD Intertie	0	0	0	0	0	0
South	Hayward Intertie	131	127	142	139	139	122
South	Jones Pumping Plant	0	0	0	0	0	0
South	Banks Pumping Plant	2	127	142	139	139	122
South	Cross Valley Canal	0	1	2	2	5	6
South	Friant-Kern Canal	0	1	1	1	1	1
South	Coastal Aqueduct	1112	1064	983	777	730	522
South	Colorado River Aqueduct	293	341	433	490	552	740
	Reservoirs ($ per TCM per year)						
North	Shasta Lake	6	7	14	16	75	87
North	Clair Engle Lake	2	2	6	7	66	75
North	Black Butte Lake	6	8	31	42	114	130
North	Lake Oroville	12	12	23	28	90	100
North	Thermalito Afterbay	7	10	19	25	97	109
North	New Bullards Bar Reservoir	15	15	29	36	108	126
North	Englebright Lake	36	36	61	71	136	151
North	Clear Lake & Indian Valley Reservoir	2	2	11	16	96	108
North	Camp Far West Reservoir	5	6	25	35	111	131
North	Folsom Lake	11	11	25	32	103	124
South	New Melones Reservoir	7	7	8	7	62	70
South	San Luis Reservoir	0	0	2	4	54	63
South	New Don Pedro Reservoir	6	6	7	7	61	69
South	Hetch-Hetchy Reservoir	4	4	5	6	61	69
South	Millerton Lake	4	5	10	11	64	74
South	Lake Kaweah	40	43	79	92	128	128
South	Lake Success	36	39	69	83	114	116
South	Lake Skinner	424	422	377	349	287	230
	Artificial recharge facilities ($ per TCM per year)						
South	Santa Clara Valley	25	543	455	498	543	759
South	Mojave	317	299	302	302	299	319
South	Antelope Valley	850	1124	1016	1072	1124	1338

[a] Minimum net Delta outflow (MNDO) (MCM per month).

[b] Some marginal values of conveyance expansion will initially increase in value because additional capacity would allow more water to be transferred, but as MNDO increases, the available supplies decrease, and additional capacity may no longer be needed because there is insufficient water to fill the conveyance facility.

[c] Hypothetical expansion from zero capacity.

conveyance facilities include the Hayward intertie, the Freeport Project, a New Don Pedro–Hetch Hetchy Aqueduct Intertie, the Friant–Kern Canal, and the Colorado River Aqueduct. Because exports are allowed, there would be modest benefit to expanding the pumping plant capacity at the SWP and CVP to allow more transfers of water south during the wet periods (when "surplus" flows remain) for use in the drier periods. As with the reduced export alternative, expanding some artificial recharge facilities for urban areas would also be beneficial (Table 9).

Expanded Surface and Underground Storage

Similar to the restricted Delta export alternative, expanding surface water storage has less value than expanding key conveyance facilities. Overall, as MNDO increases, the value of additional surface storage increases, until regulatory limits reach a point where insufficient water is available to store and still meet outflow requirements (Table 9). The largest increases in average expansion value are for reservoirs north of the Delta, followed by the San Joaquin and Tulare basins and the southern Bay Area. Southern California has the reservoir with the greatest benefit if expanded (Lake Skinner), but its value decreases as the MNDO increases because of reduced water availability.

As MNDO increases, the system must manage its groundwater and surface water more aggressively. Surface water reservoirs are drawn down further, and the range of storages increases (Figure 9). When MNDOs are high, reservoirs are filled higher when water is available, but drawn down further to supply demands. Groundwater storage also has a larger drawdown–refill cycle as MNDOs increase (Figure 9), indicating more aggressive conjunctive use.

Summary

Regulations that increase minimum Delta outflows raise water scarcity and economic costs statewide, but water transfers, changed operations, increased use of wastewater recycling and desalination, and water conservation allow users to adapt, albeit at some cost. Agricultural areas have the greatest scarcity, especially north of the Delta. Initially, they sell water south, and ultimately forgo supplies to meet Delta outflow requirements. Urban areas are relatively protected from changes in Delta outflows (except for purchasing additional water) until the highest levels of restrictions. New facilities, such as the Freeport

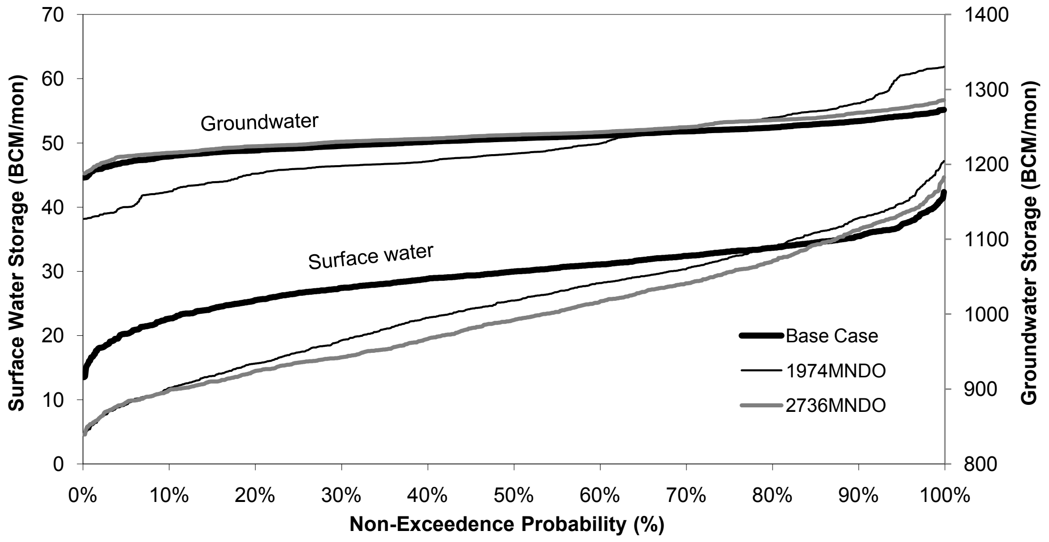


Figure 9 Statewide surface water and groundwater storage for increasing MNDO. Non-exceedence probability is the probability of having a storage volume that is below (not exceeding) the given storage volume. For example, in the base case for surface water, there is a 20% chance that storage will be less than approximately 25 BCM per month.

Project and interties to the California Aqueduct, allow urban users to replace Delta water with other sources. Overall, statewide, few major changes in scarcity occur until minimum Delta outflows exceed 1,233 MCM per month. This indicates that the state might be able to adapt to changes in outflow requirements in most periods without major impacts if flexibility in operations and transfers is already in place, and some key conveyance facilities are constructed or expanded.

COMPARING THE REGULATORY ALTERNATIVES

The two sets of model runs assessed here represent very different means of changing Delta regulations and operations. One alternative restricts exports through the pumping plants in the southern Delta, ultimately eliminating exports. The second alternative increases MNDO requirements, culminating in an outflow requirement of 32.8 BCM per year or 94% of unimpaired Delta outflows. The analysis assesses the most cost-effective way for water users to adjust to these sometimes radical changes in water availability, but the analysis does not directly consider other biological, societal, and non-economic factors that are influential in policy decisions.

Which alternative makes the most sense from a regulatory perspective depends on the regulatory objective at hand. Both alternatives reduce exports and increase Delta outflows, but do this in quite different ways (Figure 10). All else being equal (e.g., fixed urban and agricultural demands, historical hydrology, assumed costs for alternative supplies, infrastructure, etc.), eliminating exports leads to 23.1 BCM per year of net Delta outflow and an annual average cost of $4.1 billion per year—$1.5 billion higher than the costs of scarcity and operations in the base case. With the increased MNDO requirement, for the same level of Delta outflow, export pumping is at about 5.6 BCM per year and the annual average cost falls to $3.2 billion per year. Thus, the same level of Delta outflow can be achieved, while still allowing exports and the total costs are reduced by $1 billion per year.

If the regulatory objective is to limit environmental problems caused by the pumps, as in the Wanger Decision, this analysis suggests that it is most cost-effective to directly target southern Delta export activity (Figure 11). In this case, a policy to increase Delta outflows will considerably raise costs to water users, because it reduces overall water availability. In contrast, if the regulatory objective is to increase flows into and out of the Delta, the most cost effective strategy is to increase minimum Delta outflow requirements (Figure 12). Even if export users bear regulatory responsibility for this requirement, they will be able to purchase some water from agricultural areas upstream of the Delta in the Sacramento Valley and along the eastern San Joaquin Valley. This market increases water scarcity (and revenues) in the selling areas, but generates economic benefits statewide because it allows the lower-value uses of water to contribute to the solution.

At present, there may be no alternative to direct export restrictions, given the environmental threats to delta smelt (*Hypomesus transpacificus*) and other declining fish species from pumping activity. But if exports were instead routed through a peripheral canal (or similar conveyance structure), the issue of the pumps would be removed or reduced and the regulatory problem would become one of determining appropriate flows into the Delta for environmental purposes and for water quality for in-Delta users (Lund and others 2010). Whenever the objective is to increase Delta flows, the state will use its water more efficiently, with greater gains to the overall economy, if it regulates these flows directly. Market incentives can engage some participation of upstream users, even if they are not required by regulation to contribute to the higher flow requirements.

CONCLUSIONS

As Delta exports are restricted, scarcity increases for agricultural users south of the Delta. Some of these costs would be offset by revenues from sales of water by senior water-rights holders to urban areas and higher-valued agriculture. With assumed time to plan for these changes, urban deliveries are not significantly affected until exports are severely reduced (below 3.1 BCM per year). The significant increase in Central Valley and Southern California scarcity and scarcity costs when exports are curtailed highlights

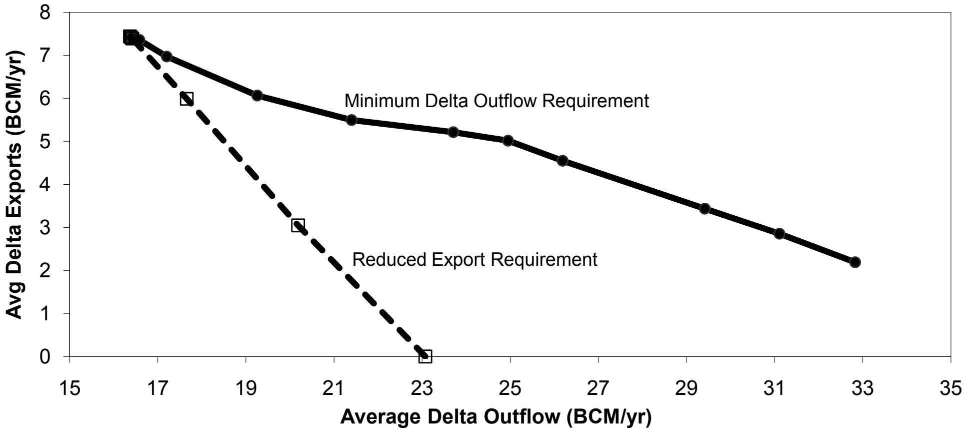


Figure 10 Average Delta exports for a given level for Delta outflow for the two alternatives: reduced export capacity and increased MNDO. As the average Delta outflow increases (from a base of about 16 BCM per year), annual average Delta export pumping decreases under both regulatory alternatives. However, exports decrease at a faster rate when export restrictions are applied. Applying a MNDO requirement is the alternative which increases average Delta outflows with the least effect on exports (as evidenced by the 'flatter' curve).

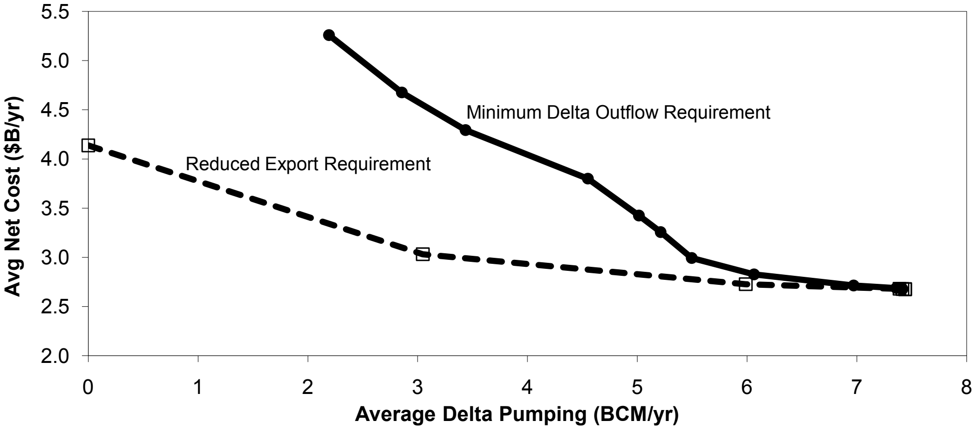


Figure 11 Average Delta export pumping and associated statewide net costs. As average Delta exports increase, average net costs decrease as more water becomes available. Changing the MNDO requirement is a more expensive means of controlling Delta exports than directly restricting export volumes. Note the "Minimum Delta Outflow Requirement" line is above the "Reduced Export Requirement" line.

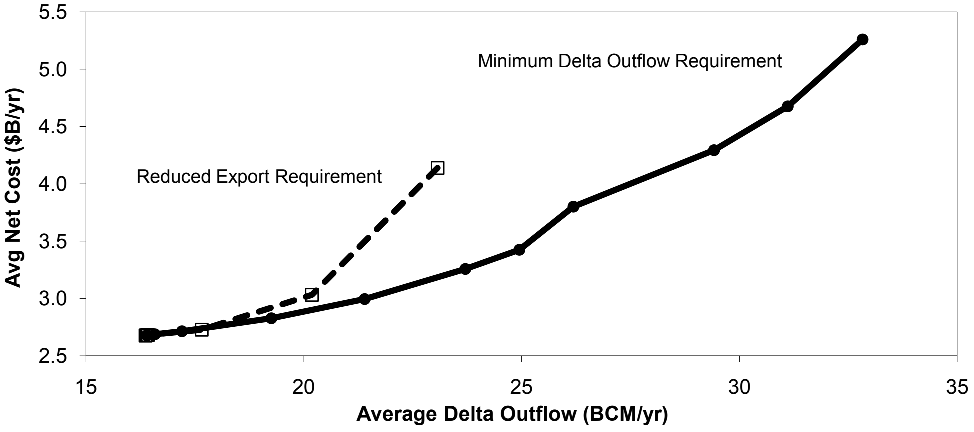


Figure 12 Average Delta outflows and associated statewide net costs. As average Delta outflows increase, the average net costs increase as water becomes scarcer and users switch to more costly supply alternatives. Generally, restricting exports is a more expensive means of increasing the average Delta outflow. Note the "Minimum Delta Outflow Requirement" line tends to be above the "Reduced Export Requirement" line.

how dependent these regions are on the Delta as a water supply source. If south-of-Delta transfers are restricted, the costs to agriculture decrease somewhat, but the costs to urban areas increase significantly, resulting in higher overall costs.

The effects of climate change were not explicitly evaluated in this study. However, previous CALVIN studies (Tanaka and others 2006; Medellín–Azuara and others 2008; Connell 2009; Harou and others 2010) demonstrate that Delta export operations are often central for economic adaption to climate change, and changes in hydrology lead to increased scarcity and costs as users adapt to reduced supplies and a seasonal shift in water availability. It seems likely that if climate warming effects, such as sea level rise and shifting hydrological timing and volumes, were added to either of the Delta regulatory alternatives examined here, scarcity and scarcity costs would increase, and the economic results (e.g., the marginal costs of environmental flows and infrastructure expansion) would be similar, though larger in absolute values.

Direct economic valuation of environmental services is controversial (Shabman and Stephenson 2000). Instead of attempting this, the marginal costs on required environmental flows were used to estimate the opportunity cost to urban and agricultural water users of various environmental requirements. Thus, as exports decrease, the opportunity cost of environmental flows increases, especially in the Central Valley. The highest opportunity costs are for flows used consumptively on site and not returned to the water system, as is the case with wildlife refuges and required consumptive lake flows (e.g., Mono Lake and Owens Lake inflows).

Additional surface water storage, while having some economic benefit, is not as valuable as expanding key conveyance and recharge facilities. Aqueducts, canals, and interties that allow users to buy and sell water, especially between the agricultural and urban sectors, are the most valuable. As export capacities are reduced, agricultural and urban users south of the Delta increase wastewater recycling and desalination to offset the reduction in surface and ground water supplies. When MNDOs are increased, urban users north and south of the Delta increase water purchasing, wastewater recycling, and eventually desalination to offset reductions in surface water and groundwater supplies.

As exports are decreased, Delta outflow increases. The increases are larger in some months (summer and fall). Depending on the management objective, having more (or alternating more and less) water flow through the Delta may be desirable (Lund and others 2007). If a freshwater Delta is the desired outcome, it is more cost-effective to increase Delta outflow requirements directly, and still allow exports. If the desired objective is a reduction in fish entrainment, then a direct reduction in exports is more efficient. A combination of Delta alternatives and management options will be needed to reduce entrainment, reduce salt water intrusion as sea level rises, and provide water supplies for agricultural and urban uses.

Overall, management of the Delta requires balancing the interests that rely on it; this includes in-Delta users, water export users, upstream diverters, and environmental concerns. Results from large system models, such as CALVIN, can help decision-makers better understand the consequences of changes in management throughout the system. While imperfect, such results produce reasoned (and reasonable) insights. Overall, California's water supply system has considerable capacity to adapt to changes in Delta water policies. While such adaptation incurs costs, it need not incur catastrophic costs statewide, if well managed.

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