Effects of Increased Delta Exports on Sacramento Valley's Economy and Water Management

By

STACY KIMIKO TANAKA
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Abstract

Exports from the Sacramento-San Joaquin Delta are an important source of water for Central Valley and Southern California users. The purpose of this paper is to analyze the effects increased pumping would have on the Sacramento Valley economy and water management if water were managed and re-allocated for purely economic benefits, as if there were an ideal Sacramento Valley water market. Current Delta exports (6,190 taf/yr) were increased to maximum export pumping plant capacities. Initial increases in Delta exports did not increase regional water scarcity, but decreased surplus Delta flows. As exports are increased further, reductions in agricultural deliveries resulted in scarcities. Urban users suffer increased scarcity only for exports exceeding 10,393 taf/yr. Expanding exports raises the economic value of expanding of key facilities (conveyance and storage) and the opportunity costs of environmental requirements.

Introduction

The Sacramento Valley, in Northern California, is home to a diverse set of water uses. The Upper Sacramento Valley is mainly comprised of agricultural users, while the Lower Sacramento Valley is more urbanized. It is also home to significant wildlife refuges and wetland areas. Over seventy percent of the state's natural runoff (from snow and precipitation) occurs North of the Sacramento-San Joaquin Delta, while most water demand occurs in the south (DWR, 1998a). Forty percent of the state's runoff makes its way into the Delta via the Sacramento and San Joaquin Rivers (DPC, 1993). The Delta provides drinking water to two thirds of the state's population and irrigation water for over 7 million acres of farmland (CALFED, 2000). Regional water planners are faced with a growing number of competing demands, both within the region and from south of Delta users. In recent decades, concerns about environmental protection and restoration have forced regional water managers to consider environmental needs along with traditional urban and agricultural demands.

Sacramento-San Joaquin Delta

The Sacramento-San Joaquin Delta is the state's largest environmental habitat. Over 750 species of plants and animals, some federally listed as threatened or endangered, live in the Delta (CALFED, 2001a). Conflicts over water allocations between and among agricultural, urban and environmental uses reached a critical impasse in the mid-1990s. Prolonged diversions and withdrawals had lead to drastically decreased native Northern California fish populations.

In 1992, the U.S. Fish and Wildlife Service began listing Delta fish species under the Endangered Species Act (ESA), limiting the operations of the Central Valley Project (CVP) and the State Water Project (SWP) (McClurg, 1996; Ploss, 1997). Under the newly proposed regulations, minimum instream flow requirements, temperature requirements, and water quality standards would have to be met to protect the endangered species (Ploss, 1997). North of Delta requirements would limit the amount of water that could be diverted to Sacramento Valley demands and in-Delta requirements would limit water exports to south of Delta demands.

The state’s two largest water supply projects, the CVP and SWP, supply water to demands both north and south of the Delta. These demands include both agricultural and urban users. The SWP’s California Aqueduct (CAA) runs from the Delta to Southern California. Likewise, the CVP’s Delta-Mendota Canal (DMC) diverts water from the Delta to agricultural and urban users in the Central Valley. Faced with federal regulation that would limit delivers from the CVP and SWP, agricultural, urban and environmental stakeholders met with federal and state agencies to formulate a plan on restoring the Delta, while maintaining water supplies (McClurg, 1994).

In December 1994 the Bay-Delta Accord, an agreement between state and federal agencies with input from agricultural, urban and environmental stakeholders, on how to better manage the Delta resources, was instituted (CALFED, 2001b). Guaranteed monthly environmental flows were agreed upon, as were means of improving system reliability for urban and agricultural demands (DWR, 1994; Gartrell, 1997; Snow, 1997). CALFED, the govern body set-up by the Bay-Delta Accords, is charged with creating and implementing long-term solutions that will protect and restore the environment and provide water for urban and agricultural demands (CALFED, 1998).

Water Markets

Among the potential solutions that CALFED has been considering are water markets (CALFED, 2000). Water markets allow for transfers between willing sellers and willing buyers. The transfers can be in the form of permanent, long-term, contingent, spot and short-term agreements. Water transfers are not new in California, but they are not extensive. Several unresolved issues limit the implementation of the water markets. The literature consistently presents three main problems with water transfers: communication between sellers and buyers, ill-defined water right and laws, and potential third party impacts (Howe et al., 1986; Brager et al., 1989; Lund and Israel, 1995; Hill, 1999).

Poor communication typically limits water transfers to intra-regional agreements. Better communications between geographically separated sellers and buyers would be required before water transfers become wide spread. Currently federal and state agencies, such as CALFED, are establishing centralized databases to facilitate transfers (CALFED, 2000).

Concerns about costs and legal implications are chief among the issues that private interest groups raise. Current legislation, they feel, is too vague and leaves sellers at the risk of losing their water rights (Hill, 1999). Buyers, on the other hand, want assurances that the amount of water they contract for will be delivered (Hill, 1999).

Third party impacts are a concern for both private and governmental groups. Impacts (externalities) include potential diminished return flows for downstream uses, environmental impacts and reduced water quality. Currently a multi-stage permitting process exists to evaluate and prevent negative externalities. Initial evaluation of potentially negative environmental impacts are dealt with during the permitting process. State law mandates that the State Water Resources Control Board (SWRCB) not approve water transfers that would negatively affect the environment (SWRCB, 1993). Impacts to other users tend to end up in court to determine if compensation is required (Howe et al., 1986). Despite the drawbacks and concerns raised, both private interest groups and the governing agencies consider water markets to be a viable solution to much of the state's water problems.

For the purpose of this paper, water markets refer to *ideal* water markets, which have no transaction costs or risks. Willing sellers and buyers have perfect knowledge of each other and the future. Reductions in scarcities and scarcity costs provide an upper bound on potential economic benefits. These results also provide a lower bound on the value of facility expansions, since the effects of droughts are somewhat dampened by perfect information.

Two additional definitions are required. In this paper, *scarcity* and *scarcity cost* are used in place of shortage and shortage cost. *Scarcity* refers to the difference in target deliveries (the deliveries at which marginal willingness to pay for one additional unit of water goes to zero) and the actual deliveries (Figure 1). *Scarcity cost* is the amount of money lost to the user because insufficient water was delivered.

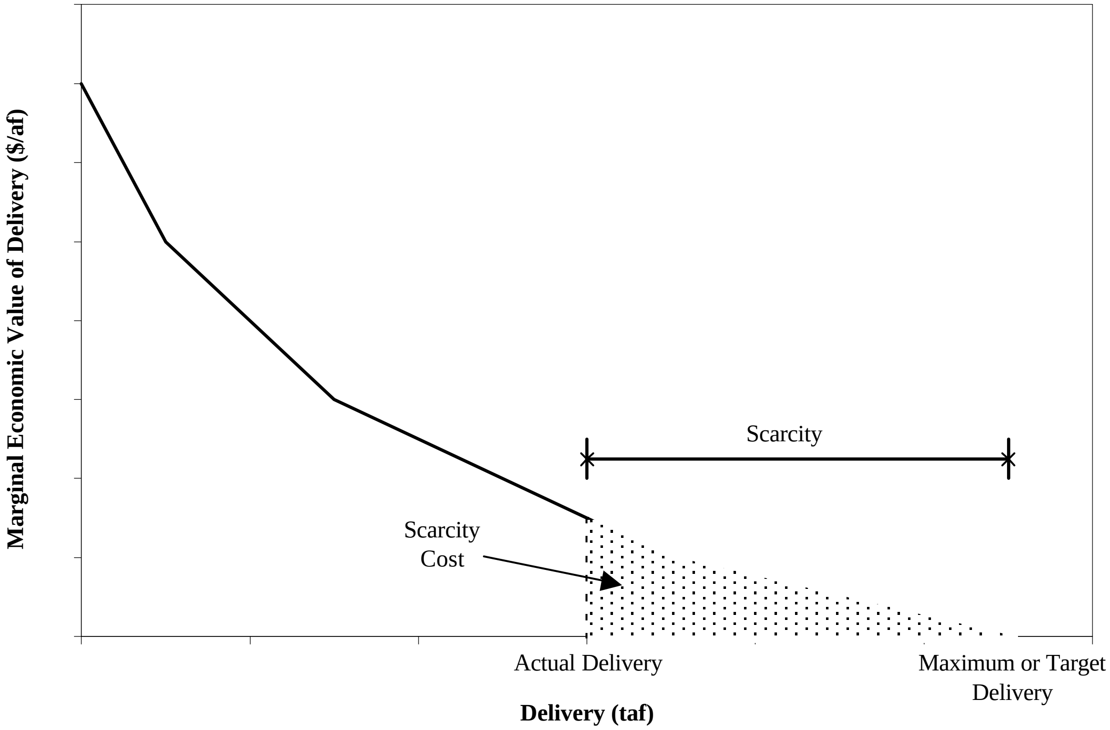

Figure 1: Scarcity Curve

Modeling Approach

Historical modeling efforts revolve around simulation models. Labadie (1997) states that "simulation or descriptive models are particularly attractive for answering *what if* questions regarding the performance of alternative operational strategies . . . [but] are ill-suited to *prescribing* the best or optimal strategies when flexibility exists in coordinated system operations." On the other hand, optimization or prescriptive models are well suited to evaluating alternatives and determining those that have the most promise. Optimization models are especially well suited to evaluating economic alternatives where the objective may be to maximizing benefits or minimizing costs. Optimization modeling has only been around for about three decades (Labadie, 1997). And up until recently large-scale optimization was nearly impossible, but advances in computers have made it increasingly feasible. There are many types of optimization models, which range from relatively simple to highly complex. Each modeling method has certain strengths and weaknesses.

One of the most common types of optimization modeling is linear programming (LP). Linear programming guarantees a global optimal solution and dual values for sensitivity analysis, among other things (Labadie, 1997). The drawback is that pure linear programming models require that the objective function and all constraints be linear. Additionally, linear programming models can be computationally burdensome. One specialized form of linear programming is network flow optimization. Network flow models represent everything as interconnected nodes. One major advantage to network flow modeling is that it can be made dynamic, allowing for multi-time period analysis.

CALVIN (<u>CAL</u>ifornia <u>V</u>alue <u>I</u>ntegrated <u>N</u>etwork) is a network-flow based economic-engineering optimization model developed by Jenkins et al. (2001 and appendices) at the University of California, Davis. CALVIN uses HEC-PRM (Hydrological Engineering Center Prescriptive Reservoir Model) a network flow optimization solver that solves for the least cost solution subject to any specified constraints (HEC, 1991).

All optimization models have certain similar characteristics: an objective function and specified constraints. The objective function specifies in mathematical terms the stated goal of the model. The objective function in CALVIN seeks to minimize the total costs to the system. These costs include penalties for below target delivers to urban and agricultural users as well as operating costs. Mathematically the objective function is:

$$\text{Minimize } Z = \sum_{i} \sum_{j} c_{ij} \, X_{ij}$$

where Z is the total cost, c_{ij} is the cost coefficient and X_{ij} is the flow from node i to node j.

The constraints represent the physical and institutional bounds that the solution is subject too. Traditional network flow modeling constraints include a “conservation equation” requiring that the flow out of node i equals the flow into node j (Ford et al., 1962). More recent network flow programming allows for gains and losses to take place on links. These network-with-gains or generalized network models have gain parameters on the links that allow for flow to be increased (Jensen et al., 1980). Parameters greater than one represents gains, while parameters less than one represent loses. CALVIN is a generalized network model that allows for gains and losses to occur on links. Constraints in CALVIN include maximum and minimum flow limits and conservation of overall mass (Jenkins et al, 2001b). Mathematically the constraints can be represented as follows:

$$\begin{array}{lll} \text{Subject to:} & \sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_j & \text{for all nodes j} \\ & X_{ij} \le u_{ij} & \text{for all arcs} \\ & X_{ij} \ge l_{ij} & \text{for all arcs} \end{array}$$

where X_{ij} is the flow from node i into node j, b_j = external inflows to node j, a_{ij} = gains or losses on flows in arc, u_{ij} = upper bound on arc, and l_{ij} = lower bound on arc (Jenkins et al., 2001b). The objective function coefficient (c_{ij}) as well as the right-hand side of the constraints are input values into the model.

Inputs to CALVIN

To represent the system to be optimized, CALVIN requires a multitude of physical and economic input parameters. Physical parameters include infrastructure capacities, hydrology and environmental requirements. Economic parameters include penalty/demand functions and operating costs (Figure 2).

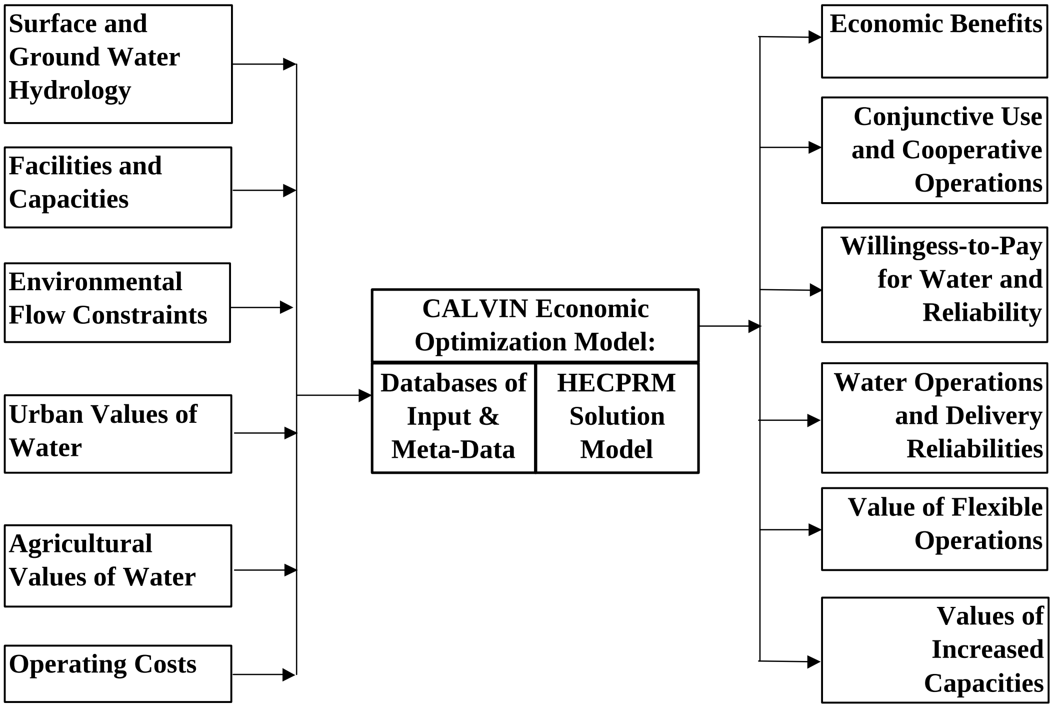

Figure 2: CALVIN Input/Output Schematic

Physical Parameters

Surface water reservoirs, groundwater basins, pumping plants, and conveyance facilities all have maximum capacities. These capacities usually vary by month, but not between years. For surface water reservoirs, maximum and minimum monthly capacities are required. The maximum reservoir capacity corresponds to the bottom of the flood storage pool. Minimum capacities correspond to the top of the dead pool. Groundwater basins only have maximum capacities.

Surface water reservoirs and groundwater basins have constrained starting and ending storage levels. This ensures that each model run has the same amount of water to allocate over the 72-year period. In addition there are minimum monthly groundwater pumping requirements because not all agricultural users have access to surface water. Return flow rates also must be specified.

Pumping plant capacities represent the maximum monthly flow that can be passed through the facility. Conveyance facility maximums also represent the monthly maximum flow that can put through the canal, tunnel, etc.

CALVIN uses 72-years worth of monthly unimpaired historical hydrology, spanning water years 1922 through 1993 and includes three of the worst drought periods on record: 1929-1934, 1976-1977 and 1987-1992 (DWR, 1998a).

Establishing economic values for environmental water uses remains controversial (Shabman and Stephenson, 2000). For this reason, environmental requirements are modeled as constraints. Minimum instream flows are modeled as lower bounds on flow links; refuge and Delta demands are fixed time series of deliveries that must be met.

Economic Parameters

Urban and agricultural users have demand curves which represent the value of water to these users. The objective function in CALVIN minimizes costs, thus the demand curves are represented by penalty functions. If full demands are met, the penalty is zero. Deliveries below full demand incur penalties. The slope of the penalty function represents the user's marginal willingness to pay. HEC-PRM requires that penalty functions be convex (increasing slope).

Operating costs are generally associated with either pumping costs (ground and surface water) or water treatment. All groundwater and surface water pumping costs are on a per-unit basis and do not vary between months. Deliveries to urban areas are subject to treatment costs, which reflect water quality. In most cases water treatment costs have a single unit cost, but deliveries to CCWD are subject to monthly varying costs (DWR, 1997).

Model Area: the Sacramento Valley

CALVIN represents most of California's inter-tied water system (supply, demand, infrastructure, etc.). The statewide CALVIN model can be sub-divided into regional models. This paper focuses on merged models of two regions (Upper and Lower Sacramento Valley and Bay Delta regions) that comprise the Sacramento Valley model (Figure 3).

As stated earlier, network flow optimization was used to model the Sacramento Valley. Optimization coordinates resources, facilities, and demands in the most economically efficient manner, as defined by the objective function. CALVIN can be easily changed to represent different alternatives or conditions and the results will identify the most promising alternatives without requiring numerous models runs.

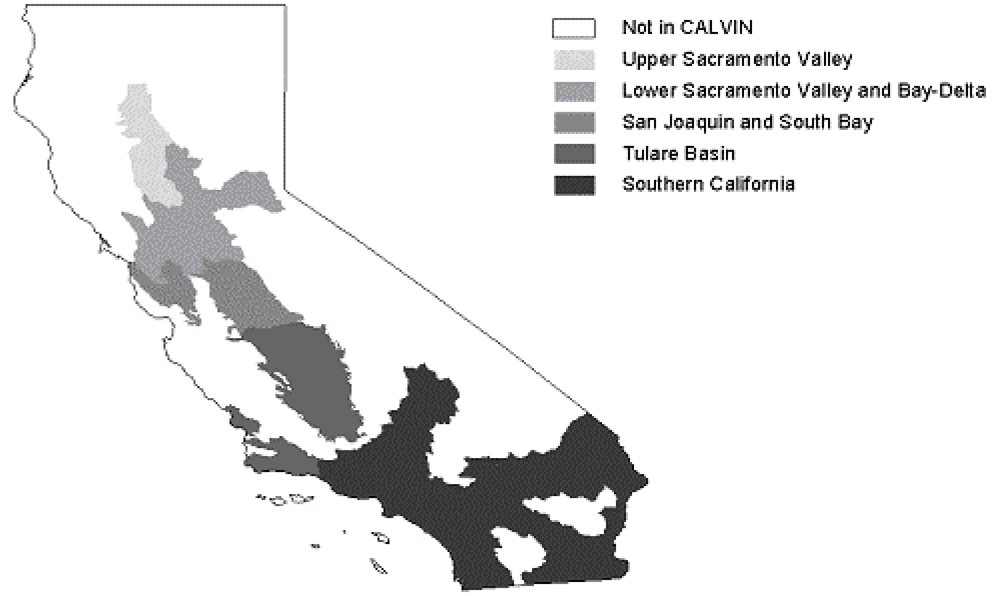

Figure 3: Sacramento Valley

For this work, the Sacramento Valley stretches from Lake Shasta and Clair Engle in the north to the Tracy and Harvey Banks Pumping Plants in the south. The model includes seventeen reservoirs and nine groundwater basins, including Lake Shasta, Lake Oroville, and Clair Engle (Trinity) which are among the largest in the state (DWR, 1998). The region's extensive conveyance facilities include the Tehema-Colusa, Glenn-Colusa, Corning, and South Folsom Canals, Mokelumne and North Bay Aqueducts, and the seven pumping plants. There are minimum instream flows on eight rivers, two aggregate wildlife refuges and required Delta outflows.

Nine agricultural demands are modeled; these correspond to the first nine Central Valley Production Model (CVPM) regions. Six urban demands are modeled economically, Greater Sacramento, Stockton, Yuba City, Napa-Solano, East Bay Municipal Utilities District (EBMUD) and Contra Costa Water District (CCWD). Ten small non-economic urban demand areas are also included in the model, served primarily by groundwater sources. Figure 4 is a small section of the Sacramento Valley model schematic. The full schematic can be viewed at http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

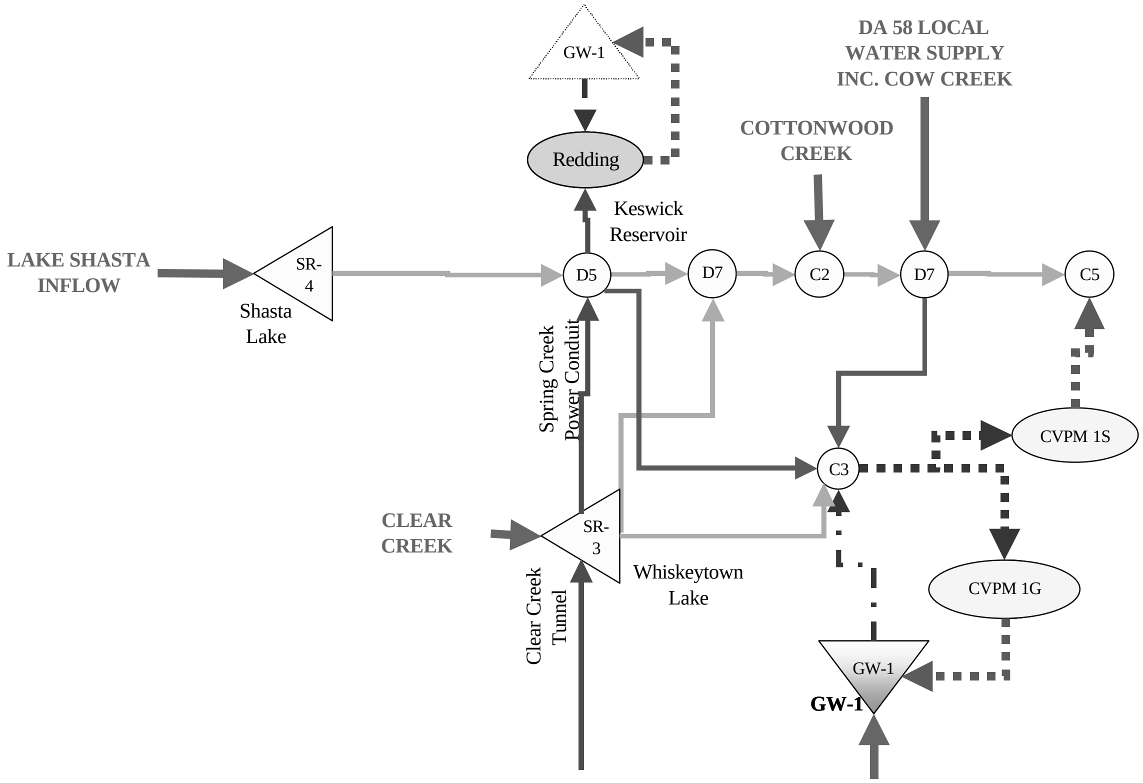

Figure 4: Representative CALVIN Schematic for the Sacramento Valley

Limitations

As with any modeling there are limitations. As mentioned earlier, perfect knowledge leads to reduced scarcity and scarcity costs by dampening the effects of droughts. Additional limitations include fixed urban and agricultural demands, lack of hydropower benefits, simplified groundwater representation and the way environmental flows are modeled (Jenkins et al., 2001).

CALVIN only uses “normal” year urban and agricultural demands, rather than varying the demands by year types. Water use efficiencies are also modeled as fixed values rather than vary by year type. Benefits from hydropower are not included in the model. If hydropower were included it would effect reservoir operations. Groundwater basins are highly simplified, primarily due to network flow optimization restrictions. Stream-aquifer interactions and deep percolation due to rainfall are not modeled in CALVIN, but rather controlled by fixed inflows based on CVGSM NAA (Central Valley Groundwater Simulation Model No Action Alternative) data (Jenkins et al., 2001). Environmental water requirements are either modeled as lower bounds or fixed times series of deliveries. CALVIN does not include, at present, minimum instream flow requirements for temperature or water quality control purposes.

Use of network flow modeling eliminates the possibility of including environmental regulations that vary depending on flow, temperature and/or water quality. This poses a severe restriction on the way in the Delta outflows are modeled. A fixed time series of outflows represent the Required Delta outflows. These do not vary depending on year type, water quality, and export-to-import ratio. The time series of outflows are replicated from the ones used by DWRSIM (Department of Water Resources Simulation Model) Run 514a (Van Lienden et al., 2001).

Modeling Alternatives

Outputs from CALVIN include the water deliveries to each demand area, flow across each link, surface and groundwater storages and marginal and shadow values at each time step for water balances and constraints. From the water deliveries, the annual average scarcity and marginal willingness to pay for each economic demand area can be calculated. Surface and groundwater storage results can suggest ways to re-operate the system for additional benefits. Marginal and shadow values on water indicate areas and facilities where changes in requirements or capacities could yield significant benefits.

All modeling alternatives examined in this paper represent the ideal regional water markets. Water operations and allocations in the Sacramento Valley are adjusted to minimize the economic losses from increased Delta exports. The exports from the Sacramento-San Joaquin Bay Delta via Tracy and Harvey Banks Pumping Plants are incrementally increased over those in DWRSIM Run 514a until pumping plant capacities are reached.

There are significant limitations associated with the representation of Required Delta Outflows. Required Delta Outflows are dependent upon a number of parameters, which include, but are not limited to, salinity levels, flow rates and export levels. The Department of Water Resources, beginning in 1995, began considering the effects of ‘carriage water.’ Carriage water is defined as the “extra water needed to carry a unit of water across the delta to the pumping plants while maintaining a constant salinity” (DWR, 1995). Carriage water representation remains a controversial issue. DWR presently models it as a function of salinity in the Delta, historical inflows and outflows from the Delta and Delta operations (DWR, 2001b). For CALVIN carriage water was modeled as a fixed percentage of the outflows above baseline export levels. One modeling alternative was made to represent maximum exports with a carriage water requirement of 33%.

Run A: Base Line

Sacramento-San Joaquin Bay Delta exports are constrained to match the results from DWRSIM Run 514. DWRSIM is a reservoir operations simulation model developed by the Department of Water Resources and Run 514 was a study performed for CALFED (DWR, 2001a).

Runs B through Q

Subsequent runs represent increased Delta Exports above baseline levels (Table 1). Decreased Delta Exports would not change the level of scarcity in Sacramento Valley and were thus omitted. Exports are limited by available pumping plant capacities in each month.

Table 1: Annual Average Delta Exports (taf/yr)

	Average Increase Over Baseline Exports	Overall[a] Annual Average Exports (taf/yr)	Drought[b] Year Annual Average Exports (taf/yr)	Percent of Months at Max Capacity
Run A	0.0%	6,190	4,097	0%
Run B	40.6%	8,706	5,939	44%
Run C	44.5%	8,944	6,203	50%
Run D	47.7%	9,144	6,458	55%
Run E	50.5%	9,313	6,701	60%
Run F	52.7%	9,454	6,930	64%
Run G	54.8%	9,581	7,142	66%
Run H	61.7%	10,008	8,048	79%
Run I	65.4%	10,240	8,723	84%
Run J	66.8%	10,325	8,995	86%
Run K	67.9%	10,393	9,217	89%
Run L	69.4%	10,485	9,524	92%
Run M	70.3%	10,544	9,740	94%
Run N	70.9%	10,582	9,899	95%
Run O	71.4%	10,608	10,007	96%
Run P	71.7%	10,630	10,100	96%
Run Q	74.3%	10,790	10,790	100%
Run R	60.3%	10,274[c] (12,285)	8,802 (11,120)	75%

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[a] Overall Annual Average refers to the 72-year average
[b] Drought Year Average refers to the average annual exports during the 14 years of drought (1929-1934, 1976-1977 and 1987-1992)
[c] 10,274 taf/yr is the volume of exports, 12,285 taf/yr is the volume of exports plus the carriage water requirement.

As exports increased, the percent of months increased when pumping plant capacities limited the effective increase in Delta Exports. For example, in Run L the maximum increase over baseline exports was 300%, but the average effective increase was only 69.4%. This is to be expected because 770 of the 864 months were at maximum pumping capacity in the previous run, leaving only 94 months to be increased in Run L. The pumping plant capacities are limiting in some months of almost all runs during the non-drought years (except for the baseline) and never binding during drought conditions until Run J.

Run R

Run R represents Delta exports with carriage water requirements. For every unit exports one-third of an additional unit was required for environmental purposes. Therefore, if 1 taf was sent to the pumping plants, in effect only 0.67 taf was exported. There was insufficient water in the system to export full pumping plant capacities and meet carriage water requirements in every month. Therefore as close to the maximum as possible is exported in each month. The results from Run R will be discussed separately from Runs A through Q.

Previous Modeling Study: Current Conditions

In a previous study conducted for CALFED, the model was used to evaluate scarcity and scarcity costs for the entire state with and without ideal water operations (Jenkins et al., 2001). Under current contractual and legislative requirements (non-ideal water operations), the Sacramento Valley would experience nearly 171 taf/yr of scarcity (152 taf/yr is to agricultural users and 19 taf/yr is to urban users) and $42.3 million per year ($6.8 million per year to agricultural users and $35.5 million per year to urban users) in scarcity costs (Tanaka et al, 2001a; Tanaka et al., 2001b). South of Delta results indicated that if an ideal water market or some other form of economically efficient water operations were instituted, South of Delta users could reduce scarcity and scarcity costs without needing additional Delta Exports.

Model Results

This section presents selected Sacramento Valley model results. Agricultural and urban water deliveries are presented first, followed by agricultural and urban scarcity results. Environmental water requirements are presented next. Then regional economic value of water is presented. This includes the Sacramento Valley marginal costs of Delta exports and the shadow values on environmental flows. Conjunctive use and cooperative operations are then discussed. Finally, some conclusions are presented.

Water Delivery Results

As shown in Figure 5, as exports increase beyond 9 maf/yr, regional water scarcity and scarcity costs increases. Until exports reach 10,393 taf/yr the additional scarcity due to the increased exports is limited to the agricultural regions. One urban area (EBMUD) sees a fixed scarcity regardless of the exports level, due to a combination of capacity constraints and limited inflow during drought periods (Jenkins et al, 2001). Exports in excess of 10,393 taf/yr result in additional urban scarcities. The environmental demands are always constrained to be met. However, environmental flows above these required levels see sharp reductions with increased exports.

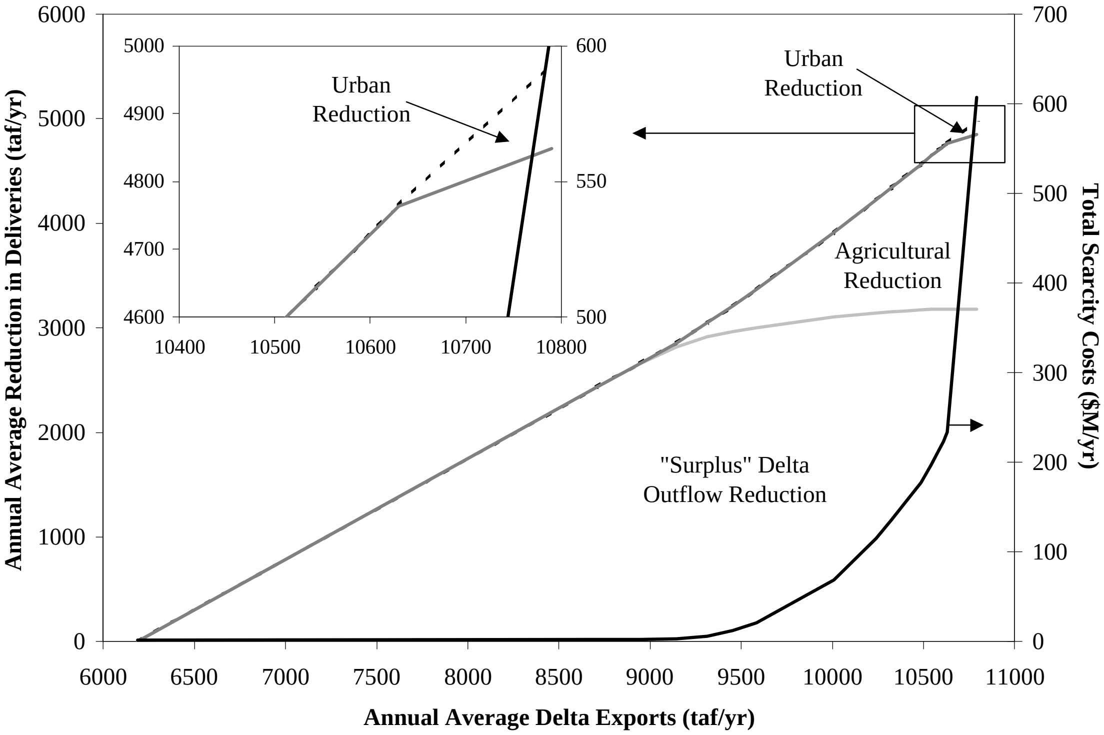

Figure 5: Annual Average Reduction in Deliveries (taf/yr) and Scarcity Costs ($M/yr)

Agricultural Scarcity

With exports above 9,144 taf/yr agricultural scarcity increases with increased Delta Exports. Agricultural water generally has less economical value than urban water, so increases in agricultural scarcity occur before increases in urban scarcity. The nine Sacramento Valley agricultural areas see varying levels of scarcity with increased Delta Exports. With baseline exports only agricultural users in the Delta (CVPM 9) experience water scarcity. CVPM 9 remains the only region experiencing scarcity until exports exceed 9,144 taf/yr (Run D), at which point almost all agricultural regions see reduced deliveries (Figure 6). Even during the fourteen drought years, overall agricultural scarcity is not greatly affected until exports exceed 9,144 taf/yr (Run D).

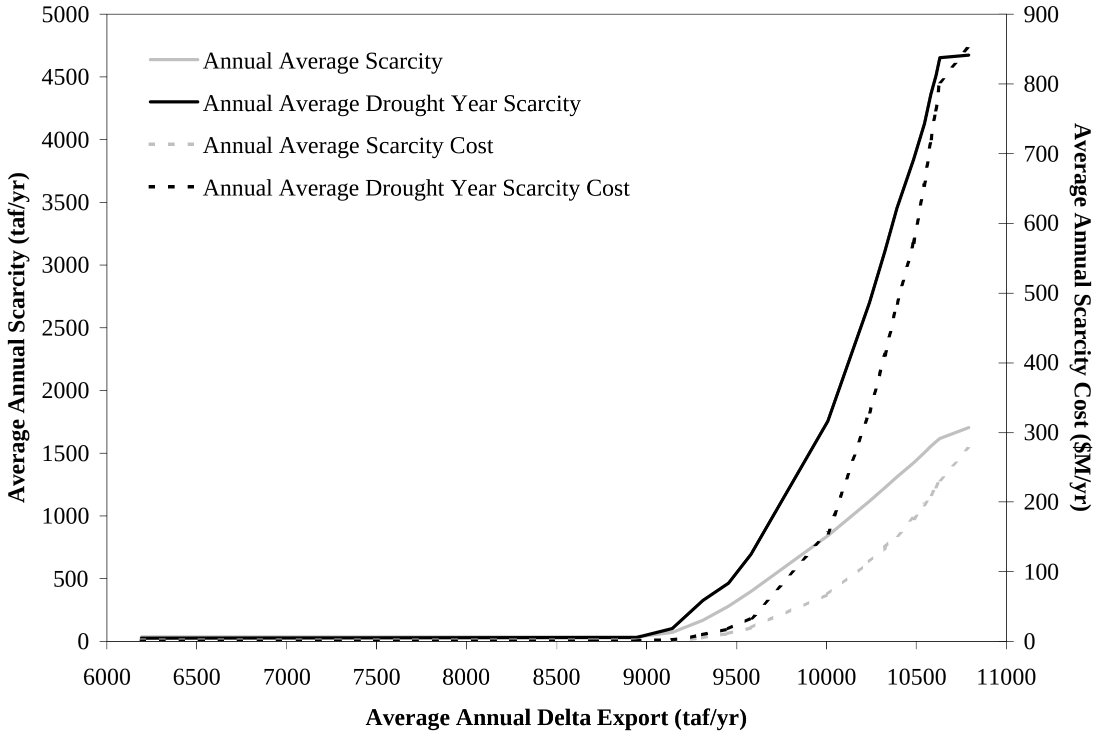

Figure 6: Average Annual Agricultural Scarcity (taf/yr) and Scarcity Costs ($M/yr)

As Delta exports increase, agricultural users would face significant scarcity costs (especially during drought years). With baseline exports, the 72-year average cost of agricultural scarcity is $1.5M/yr. Increasing exports to approximately 9,581 taf/yr on average, raises annual average scarcity cost to $20 million ($34 million in drought years). Drought year scarcity costs could exceed $800M/yr if exports were increased to the maximum pumping capacity (Figure 6). Operating costs (groundwater pumping only) range from $73.7M/yr at baseline exports and decrease to $70.6M/yr at maximum capacity exports (reflecting decreased deliveries).

As exports increased, the marginal value of additional water also increased. Initially, only CVPM 9 had any willingness to pay for additional supplies averaging $11.0/af. As additional agricultural areas began to experience scarcities, the maximum willingness to pay for additional water supplies also increased. At export levels of 10,790 taf/yr, marginal willingness to pay for additional deliveries is $113.2/af. As expected, as exports increased, the marginal willingness to pay increased during drought years to greater values. See Figure 7 for details.

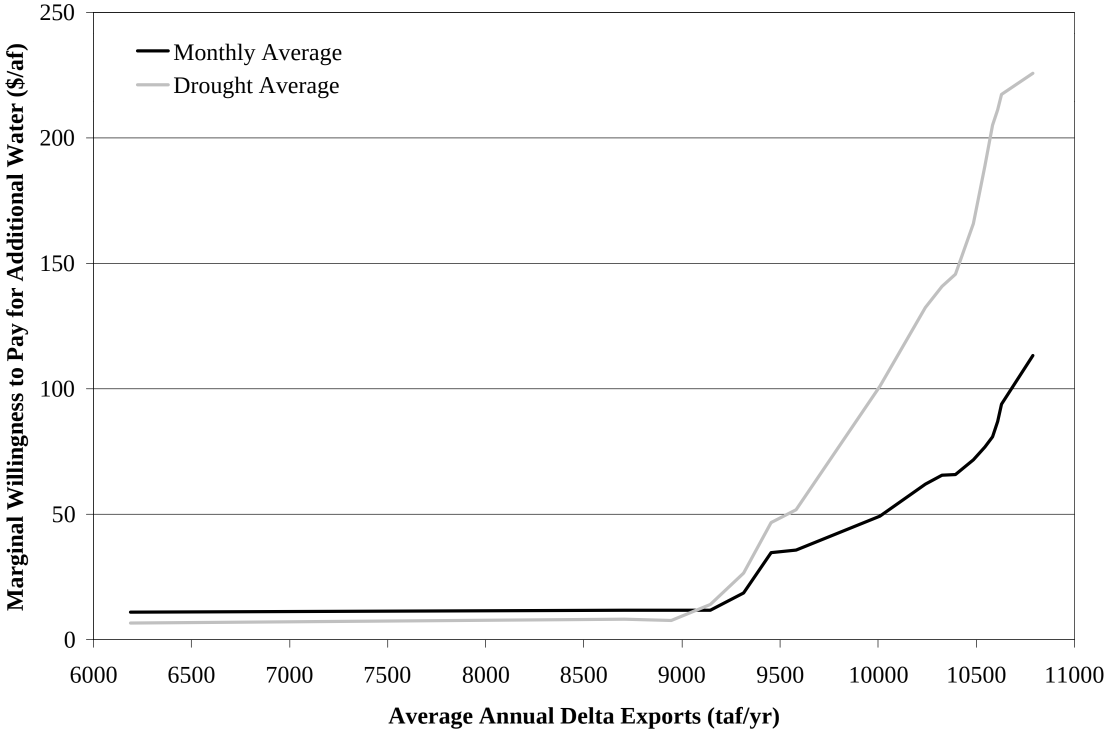

Figure 7: Agricultural Marginal Willingness to Pay for Additional Water ($/af)

Urban Scarcity

At baseline exports, only EBMUD experiences urban water scarcity, due to a combination of low drought (1976-1977) inflows, binding capacity constraints on local storage and lack of other water sources. Thus, decreasing Delta exports below the baseline levels would not reduce EBMUD’s scarcity. There is a small scarcity during the non-drought years, but in general the urban areas (EBMUD and later Yuba) only see an increase in scarcity during the drought years. Once annual average exports exceed 10,325 taf/yr (Run J) other urban areas begin to see scarcity. Yuba is the first, with small scarcities of less than 0.5 taf/yr. Again, like EBMUD most scarcities occur during the critically dry periods (Figure 8).

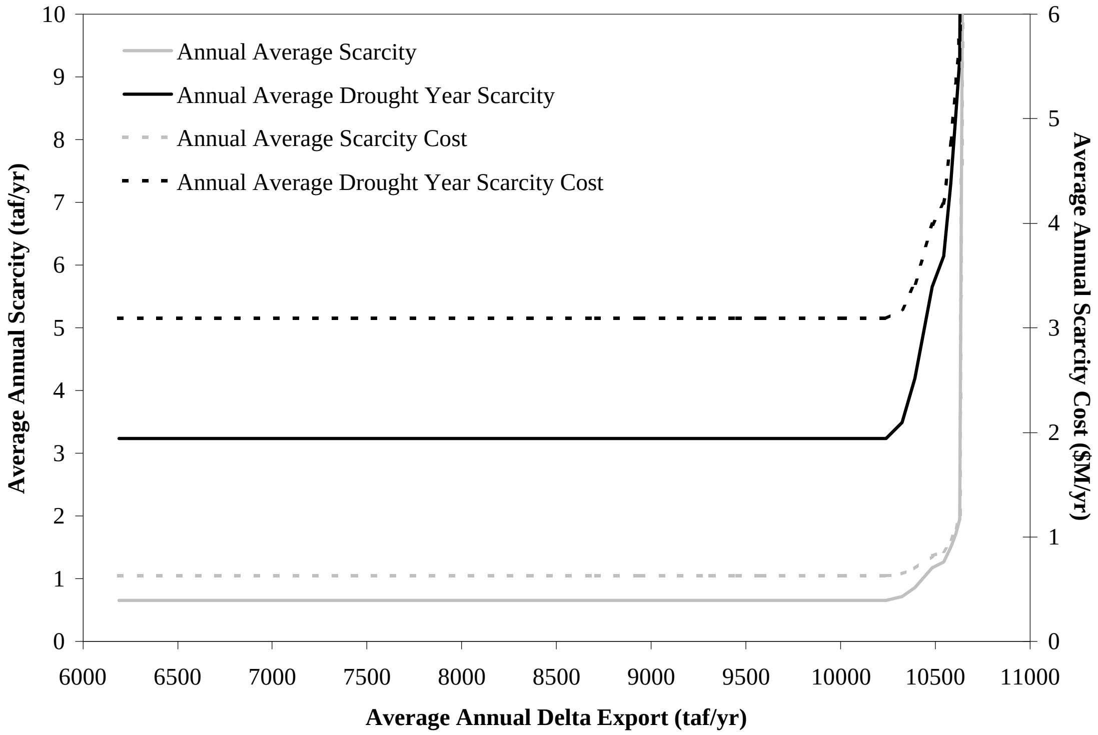

Figure 8: Annual Average Urban Scarcity (taf/yr) and Scarcity Costs ($M/yr)

Even small volumes of scarcity incur significant costs for urban areas. The 0.7 taf/yr scarcity to EBMUD on average translates to a $630K/year ($953/af) scarcity cost (Figure 8). Urban scarcity costs are smaller than agricultural scarcity costs, but on a unit volume basis, the cost of scarcity is much more severe in urban areas. If exports were increased to export pumping capacity, annual average urban scarcity increased to 125.9 taf/yr (587.7 taf/yr during droughts). The resulting scarcity cost was $331M/yr ($1534M/yr during droughts). Operating costs (pumping, water treatment and conveyance) range from $123.6M/yr at baseline exports, increase to a maximum of $126.9M/yr as more expensive sources are utilized, then drop at maximum exports to $115.3M/yr, due to reduced deliveries.

The marginal value of additional water to urban areas remained unchanged until exports exceeded 10,325 taf/yr. Initially only EMBUD ($27.6/af) had any willingness to pay for additional supplies. As additional urban areas began to experience scarcities, the maximum willingness to pay for additional water also increased. At export levels of 10,790 taf/yr, the maximum marginal willingness to pay for additional deliveries is $1,048.1/af. See Figure 9 for details.

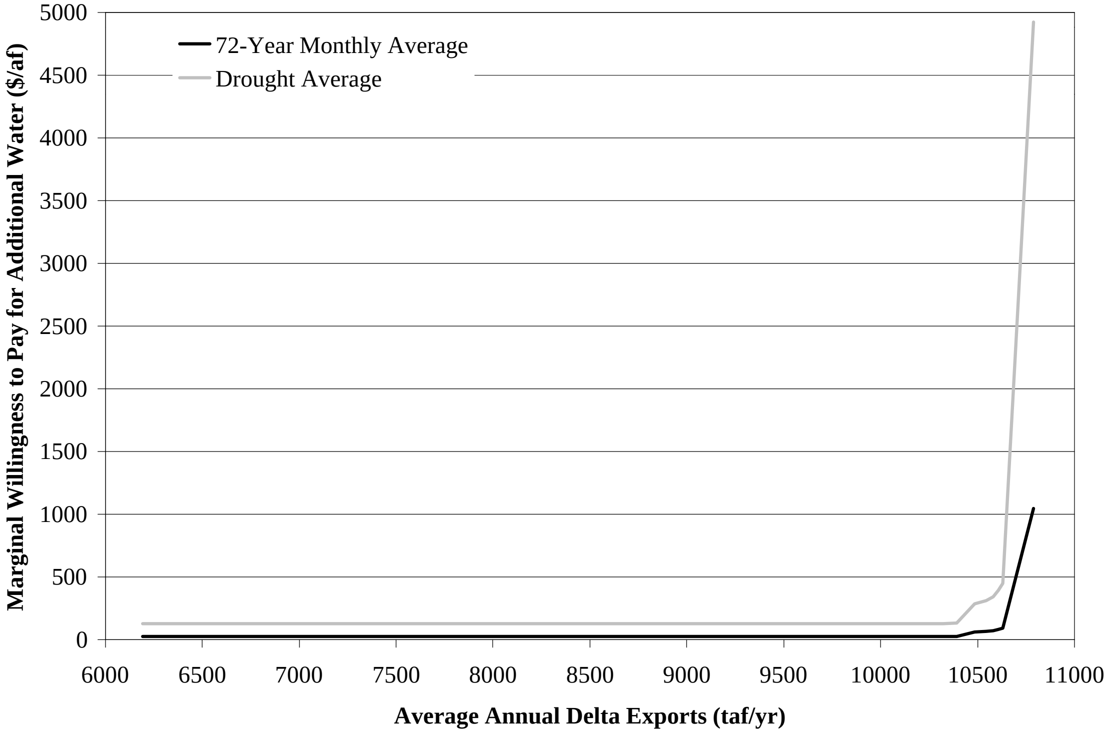

Figure 9: Urban Marginal Willingness to Pay for Additional Water ($/af)

Environmental Water Use

The Sacramento Valley has some of California's largest environmental water requirements. Table 2 lists the minimum instream flows for the region. These requirements vary from month to month and year to year.

Table 2: Environmental Minimum Instream Flow Requirements

River	Maximum Annual Average (taf/yr)	Drought Average (taf/yr)
Clear Creek	41.8	40.4
Sacramento River	3619.5	3619.5
Feather River	936.5	838.9
Yuba River	170.3	142.6
Mokelumne River	87.6	29.3
Calaveras River	1.2	1.2
American River	1076.2	643.4

Trinity River	348.7	348.7

The Sacramento Valley also has two wildlife refuges. The Sacramento, Delevan and Colusa Wildlife refuges are aggregated into the Sacramento West Refuge. The Sutter National Wildlife Refuge and the Gray Lodge Wildlife Area are aggregated into the Sacramento East Refuge. The USBR has identified levels of deliveries shown in Table 3 as optimal management of wildlife (USBR, 1997a; USBR, 1997b). These monthly varying deliveries were imposed for this model.

Table 3: Refuge Requirements

River	Deliveries (taf/yr)
Sacramento WR	50,000
Delevan WR	30,000
Colusa WR	25,000
Sacramento West Refuge	**105,000**
Sutter NWR	30,000
Gray Lodge WA	44,000
Sacramento East Refuge	**74,000**

The final environmental water requirement is required Delta Outflows. The Delta requirement is modeled as a fixed time series, averaging 5,593 taf/yr (4,087 taf/yr during the droughts), constrained to match the results from DWRSIM Run 514a. These requirements are enforced and met before any economically driven demands in all model alternatives. In addition CALVIN can divert any surplus water in the system to Delta Outflows.

As exports increase, surplus Delta outflows decrease (Figure 10). During the winter months there is water in excess of the export requirements, which result in Surplus Delta outflows. However, in the summer the excess flows are severely limited, which reduces the Surplus Delta outflows. Even with maximum exports, significant outflows remain in the winter months, while surplus summer outflows decrease to nearly zero (Figure 11). Once Delta Exports exceed 9,581 taf/yr (Run G), there is no significant reduction in the Surplus Delta Outflows as exports increase.

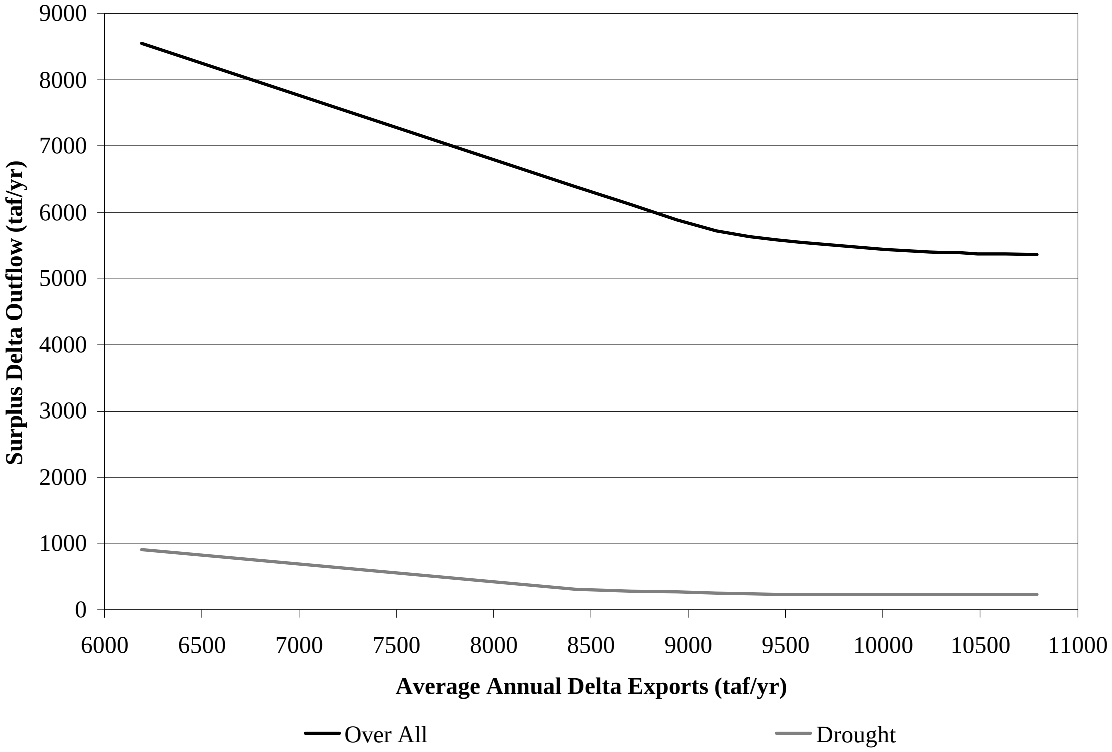

Figure 10: Surplus Delta Outflow

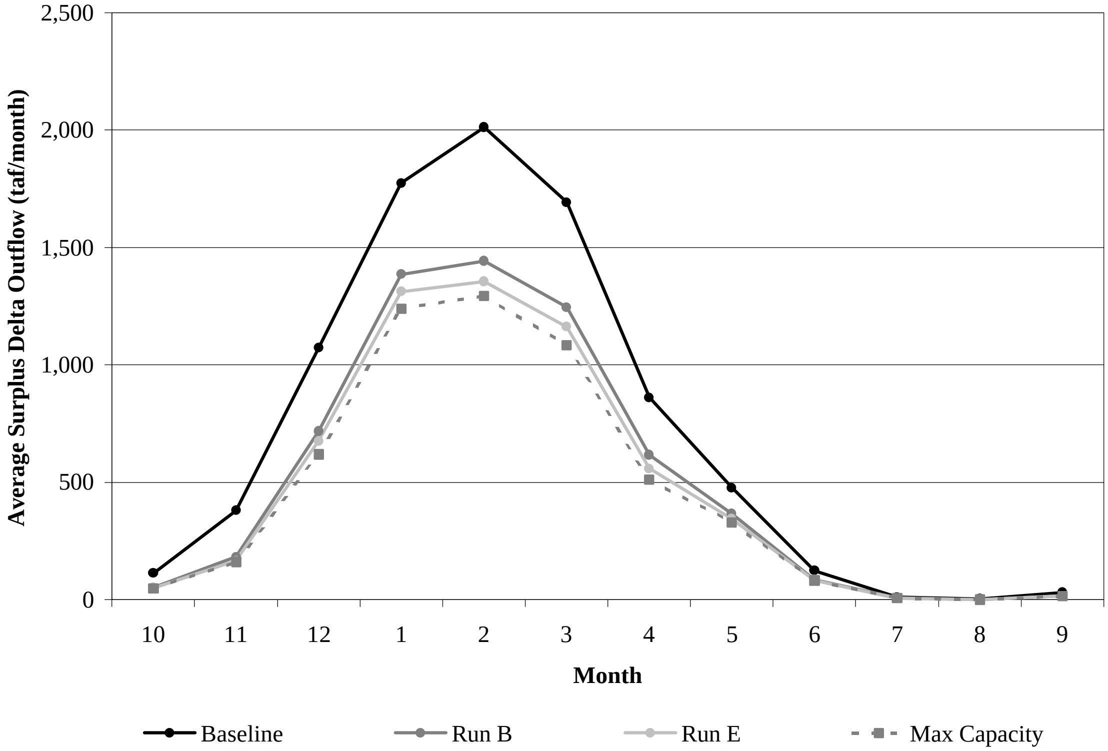

Figure 11: Monthly Surplus Delta Outflows (taf/month)

Marginal Economic Costs of Delta Exports

All model runs had some water scarcity, but initial scarcities were not due to the Delta Exports, but from constraints internal to the Sacramento Valley. This is reflected in the low marginal costs of Delta Exports (Figure 12). As exports increased, the marginal costs also increased.

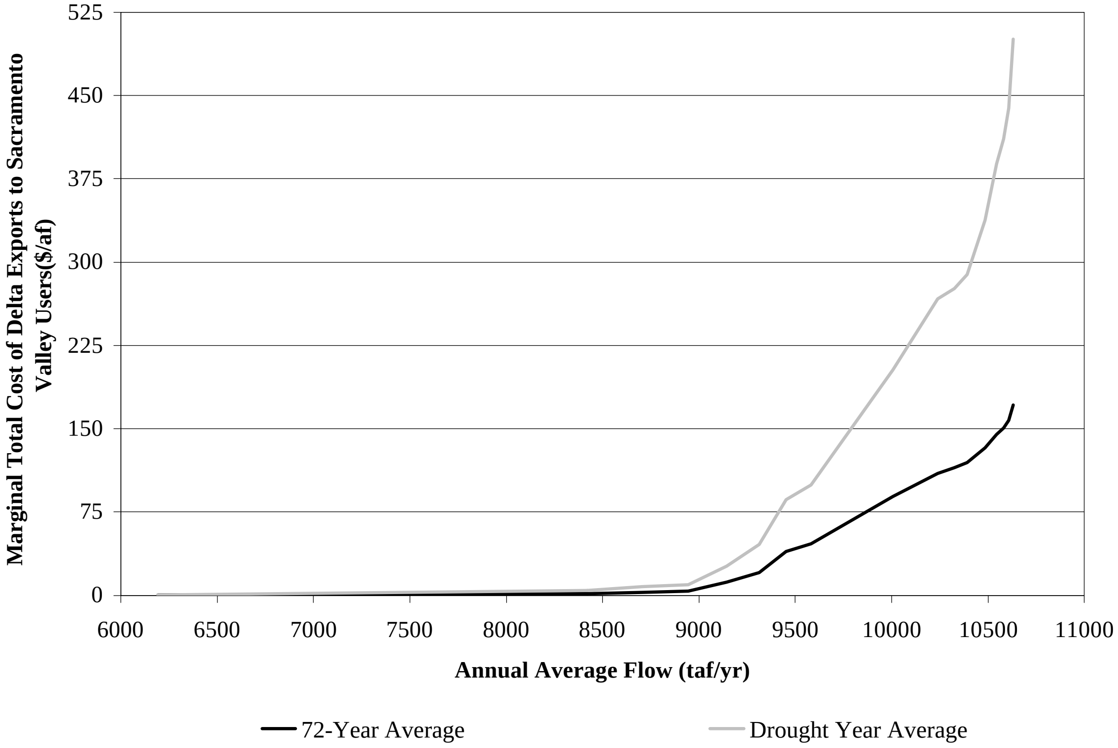

Figure 12: Marginal Total Cost of Delta Exports to Sacramento Valley Users ($/af)

Marginal cost of Delta Exports increase drastically as exports exceed 9,581 taf/yr, the point where additional agricultural scarcities occur. The marginal cost is especially high during drought years. When exports are increased to the maximum possible (10,790 taf/yr), the monthly average marginal cost increases to $1,846/af ($8,279/af during the drought).

Shadow Values on Environmental Flows

Minimum instream flows do not usually limit water operations and allocations. However as exports and scarcities increase, the minimum instream flows become more limiting more frequently to produce increased shadow values. See Table 4 and 5 for details. The highest shadow values are for the Trinity River minimum flows. This requirement has the most direct effect on the system because it directly reduces water available to the system, without opportunity to recapture some of the flows downstream.

The two refuges and required Delta outflows do not initially produce significant costs to Sacramento Valley urban and agricultural users, but like the minimum instream flows, greater exports and scarcities increase shadow values. Initially the highest shadow values appear for the Sacramento West Refuge, which diverts water from CVPM 3. However, as exports increase, the shadow values on the Required Delta Outflows begin to dominate. At maximum export pumping capacities, the two greatest shadow values are on the Trinity River minimum flows ($,1948/af) and the Required Delta Outflows ($1,564/af). During drought periods, the shadow values increase for most of the requirements. As expected, the Trinity River minimums and Required Delta Outflow again have two of the greatest values to reduction ($8,748/af and $7,198/af, respectively).

Table 4: Marginal Value on Environmental Flows, Storage and Conveyance Facilities ($/af)

Effective Increase (%)	0.0	40.6	44.5	47.7	50.5	52.7	54.8	61.7	65.4	66.8	67.9	69.4	70.3	70.9	71.4	71.7	74.3
Minimum Instream Flow Marginal Values ($/af)																	
Clear Creek	0.3	0.5	0.6	1.4	2.2	3.9	4.5	8.1	9.8	10.1	10.4	11.4	12.6	13.1	13.6	14.6	99.4
Sacramento below Keswick	0.2	0.4	0.5	1.3	2.1	3.8	4.4	8.0	9.7	10.0	10.3	11.3	12.5	13.0	13.5	14.4	98.3
Feather River	0.1	0.3	0.4	1.2	2.0	3.8	4.4	8.0	9.8	10.0	10.3	11.3	12.3	12.7	13.2	14.2	109.7
American River	0.0	0.1	0.1	0.3	0.5	0.8	1.1	2.2	2.6	3.2	2.9	4.1	4.2	3.5	4.0	5.4	50.2
Sacramento in the Delta	0.0	0.4	0.5	1.6	2.9	5.5	6.2	11.7	14.5	15.2	15.9	17.9	19.4	20.2	21.1	23.1	280.3
Mokelumne River	0.1	7.6	7.6	7.8	8.0	8.0	7.8	13.6	16.2	16.7	17.4	19.7	22.2	23.3	24.8	27.0	220.2
Trinity River	0.8	3.3	4.3	12.9	22.8	43.5	50.6	96.6	119.5	124.4	129.4	144.0	157.5	163.6	170.7	185.7	1947.6
Refuges & Delta Marginal Values ($/af)																	
Sac East Refuge	0.2	2.6	3.4	11.1	20.2	38.9	45.3	87.1	107.5	110.6	112.6	117.4	118.7	120.0	122.8	126.2	120.0
Sac West Refuge	0.5	3.2	4.3	13.6	24.4	47.0	54.6	104.9	129.8	135.2	139.6	145.8	149.8	151.6	153.5	156.5	598.5
Required Delta Outflows	0.2	2.2	3.0	9.7	17.6	33.9	39.7	76.6	94.9	98.8	102.8	114.3	125.2	130.0	135.6	147.7	1564.0
Reservoir Marginal Values ($/af)																	
Folsom	0.0	0.1	0.2	0.4	0.8	1.5	1.8	3.2	3.9	4.1	4.3	4.7	5.1	5.2	5.4	5.9	59.3
Black Butte	0.2	0.3	0.3	0.7	1.2	2.2	2.5	4.4	5.3	5.4	5.6	6.1	6.6	6.8	7.1	7.6	65.8
Camp Far West	0.0	0.1	0.2	0.5	0.8	1.5	1.8	3.3	4.1	4.2	4.4	4.8	5.2	5.3	5.5	6.0	60.5
Englebright	0.0	0.2	0.3	0.9	1.5	2.9	3.4	6.4	7.8	8.1	8.4	9.3	10.2	10.5	10.9	11.8	101.8
Conveyance Marginal Values ($/af)																	
Corning Canal	0.2	1.2	1.6	4.5	8.0	14.3	15.6	20.0	19.7	19.3	19.2	18.9	18.6	18.6	18.6	18.6	18.6
Los Vaqueros PMP	0.1	0.2	0.3	0.8	1.2	2.3	2.8	5.4	6.5	6.7	6.9	7.5	8.3	8.6	9.0	9.6	57.1
Napa Recycling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	6.4	9.4	20.3	32.2	38.0	44.7	59.4	1643.8
CCWD Recycling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.6	3.0	12.1	22.6	27.3	32.9	46.2	990.1
EBMUD Recycling	20.2	20.2	20.2	20.2	20.2	20.2	20.2	24.1	42.3	46.3	51.1	65.9	80.1	86.8	94.4	108.4	905.1
Proposed Folsom S. Canal Extension	26.0	32.5	32.3	31.7	31.8	32.5	38.8	59.1	52.0	54.9	54.2	69.6	61.1	68.7	68.5	97.8	995.3
Mokelumne-CCWD Connector	85.4	93.5	93.3	92.8	92.4	91.3	90.7	94.1	95.2	96.1	96.9	98.9	101.0	102.1	103.2	103.4	273.8

Table 5: Drought Year Marginal Values on Environmental Flows, Storage and Conveyance Facilities ($/af)

Effective Increase (%)	0.0	40.6	44.5	47.7	50.5	52.7	54.8	61.7	65.4	66.8	67.9	69.4	70.3	70.9	71.4	71.7	74.3
Minimum Instream Flow Marginal Values ($/af)																	
Clear Creek	1.0	1.1	1.3	2.3	3.1	5.2	6.0	12.1	16.2	16.7	17.8	21.6	25.7	27.8	30.1	34.2	455.7
Sacramento below Keswick	0.5	0.7	0.9	2.0	2.9	5.1	5.9	12.0	16.0	16.6	17.6	21.4	25.6	27.5	29.8	34.0	450.7
Feather River	0.1	0.6	0.7	1.8	2.8	5.1	5.9	11.9	15.9	16.5	17.4	20.8	24.8	26.5	28.5	32.6	458.9
American River	0.1	0.2	0.3	0.6	1.1	1.7	1.9	3.9	5.4	5.4	7.6	11.1	10.5	8.9	9.8	17.6	245.4
Sacramento in the Delta	0.0	0.8	1.0	3.1	5.7	10.7	12.1	24.5	32.3	33.5	35.1	41.9	47.5	50.2	53.7	61.6	1081.0
Mokelumne River	0.3	30.4	30.1	26.4	22.5	13.0	8.7	13.6	17.2	17.8	18.9	25.2	31.2	32.6	35.2	41.0	559.4
Trinity River	1.9	7.4	9.7	27.2	47.9	90.9	105.7	215.4	283.6	293.2	307.2	359.3	414.5	439.1	468.8	535.6	8748.0
Refuges & Delta Marginal Values ($/af)																	
Sac East Refuge	0.4	5.9	8.0	24.3	44.1	84.4	98.3	200.3	261.4	263.4	263.5	270.7	268.1	270.0	279.5	291.3	168.0
Sac West Refuge	0.9	7.3	9.8	29.4	53.0	101.5	118.2	240.6	315.7	325.8	335.6	345.8	354.1	357.7	362.0	370.8	2223.7
Required Delta Outflows	0.4	5.2	7.0	21.5	39.0	74.8	87.4	178.5	234.8	242.6	253.9	295.4	340.8	360.6	384.6	439.1	7197.5
Reservoir Marginal Values ($/af)																	
Folsom	0.0	0.1	0.1	0.2	0.4	0.9	1.1	2.5	3.5	3.6	3.8	4.8	6.0	6.5	7.2	8.7	226.5
Black Butte	0.2	0.3	0.3	0.6	0.9	1.6	1.9	3.9	5.4	5.6	5.9	7.0	8.8	9.5	10.3	12.2	253.1
Camp Far West	0.0	0.1	0.1	0.3	0.6	1.1	1.3	2.7	3.8	3.9	4.2	5.1	6.4	6.9	7.6	9.2	231.3
Englebright	0.1	0.3	0.4	1.2	2.0	3.8	4.4	9.0	12.1	12.5	13.2	15.6	18.9	20.3	21.9	25.4	427.1
Conveyance Marginal Values ($/af)																	
Los Vaqueros PMP	0.1	0.3	0.4	1.0	1.5	3.4	4.1	8.4	11.0	11.4	12.0	14.4	17.7	19.1	20.6	23.4	258.5
Napa Recycling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.9	27.8	40.9	89.8	143.7	169.2	198.5	264.1	7699.4
CCWD Recycling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	7.4	13.9	57.7	108.8	131.3	158.0	221.4	4701.7
EBMUD Recycling	99.3	99.3	99.3	99.3	99.3	99.3	99.3	115.7	175.6	184.8	198.4	252.1	308.9	332.2	359.9	419.5	3856.0
Folsom S. Canal Ext.	127.5	156.1	155.0	149.3	143.2	134.2	148.1	183.4	143.2	147.3	114.2	217.9	145.9	173.5	167.0	299.4	4319.4
EBMUD-CCWD Connector	184.4	216.9	215.8	209.2	202.1	186.2	179.4	169.5	165.2	165.9	166.9	172.0	177.3	177.7	177.9	173.9	598.1

Economic Value for Expanded Storage

All seventeen reservoirs modeled in the Sacramento Valley have some value to expansion, especially during drought years. However, the values of expansion are small compared to the shadow values on refuge deliveries and required Delta outflows. The largest value to expansion comes from Englebright Lake on the Yuba River, which has a maximum average value of $101.8/af, increasing to $427.1/af during drought years. Three additional reservoirs had value to expansion: Folsom Lake on the American River, Camp Far West Reservoir on the Bear River and Black Butte Lake on Stony Creek, all with similar marginal values (Tables 5 and 6). Major storage facilities like Shasta and Oroville have value to expansion both during drought and non-drought years, but the value is below $50/af at maximum exports.

A sharp increase in value to storage (primarily during drought years) results from urban scarcity that occurs with high levels of Delta Exports. The relatively small value to storage expansion with lower exports indicates that water scarcity is not related to system's ability to store water.

The groundwater basins are either constrained to their physical or institutional capacities. Institutionally constrained basins could be expanding by changing the volume legally allowed to be withdrawn. Increasing the usable volume, such as by digging deeper wells could expand the physically constrained groundwater basins. However, none of the groundwater basins have significant value to capacity expansion. There is value to increasing (or decreasing) the volume of groundwater stored in a given basin, but not to expanding the basin's maximum usable capacity.

Note that these shadow values do not include value of hydropower for increasing storage capacities, increasing head and operational flexibility to release at peak times. Also perfect foresight operations in CALVIN can depress the economic values of facilities overall.

Economic Value of Conveyance and Other Facility Expansion

The potential economic value of expanding other types of existing and proposed facilities also can be estimated using shadow price model results (Table 4 and 5). Initially the expansion of the Corning Canal would yield the largest conveyance expansion benefit. It would enable CVPM 2 to divert more water from the Sacramento River, reducing Tehema-Colusa Canal diversions and groundwater pumping. However, it reaches a maximum of $18.9/af. After this, the expansion of the Los Vaqueros’ pumping plant yields the greatest economic benefits to the system (Table 4 and 5).

Of the recycling facilities, initially only EBMUD’s recycling facility has any expansion value ($20.2/af/yr), enhancing supplies during critically dry periods. As Delta exports increase and additional urban demand areas begin to experience scarcities (or are forced to use higher cost sources) expanding recycling facilities becomes more valuable. At maximum export levels, several recycling plants show great benefits.

The proposed extension of the Folsom South Canal and a Mokelumne Aqueduct-Contra Costa Canal Connector would provide great benefits to the system. The Connector would enable CCWD to import higher quality Mokelumne River water, reducing their annual operating costs and enable EBMUD to import additional supplies during critically dry periods. The Folsom South Canal Extension would also enable EBMUD to diversify its supplies.

Conjunctive Use

Conjunctive use refers to the coordinated use of both surface and groundwater sources. All agricultural users and only two urban areas (Greater Sacramento and Stockton) have access to groundwater. Sacramento and Stockton share access to groundwater basins with CVPM 7 and 8. The enforced minimum monthly agricultural groundwater pumping levels, prevent groundwater withdrawals by the agricultural regions from changing radically as Delta Exports increase. Both types of users increase groundwater pumping during the droughts to offset diminished surface water availability.

In general as exports increase, groundwater use increases up to the 1960's. Groundwater pumping significantly increases prior to and during the 1929-1934 drought. The ending constraint on groundwater storage ensures that there is a constant volume of water available between model run. As a result the increased pumping prior to the 1960's must be offset by decreased pumping after the 1960's (Figure 13). Annual average groundwater storage varied by a maximum 1.7 maf/month (Run K) and by 2.3 maf/month during droughts (Run G) from baseline conditions. Surface water use, in general, increased with increasing Delta Exports (Figure 14). The maximum difference in surface water storage from the baseline levels was 3.7 maf/month (Run H) overall and 5.6 maf/month (Run H) during droughts.

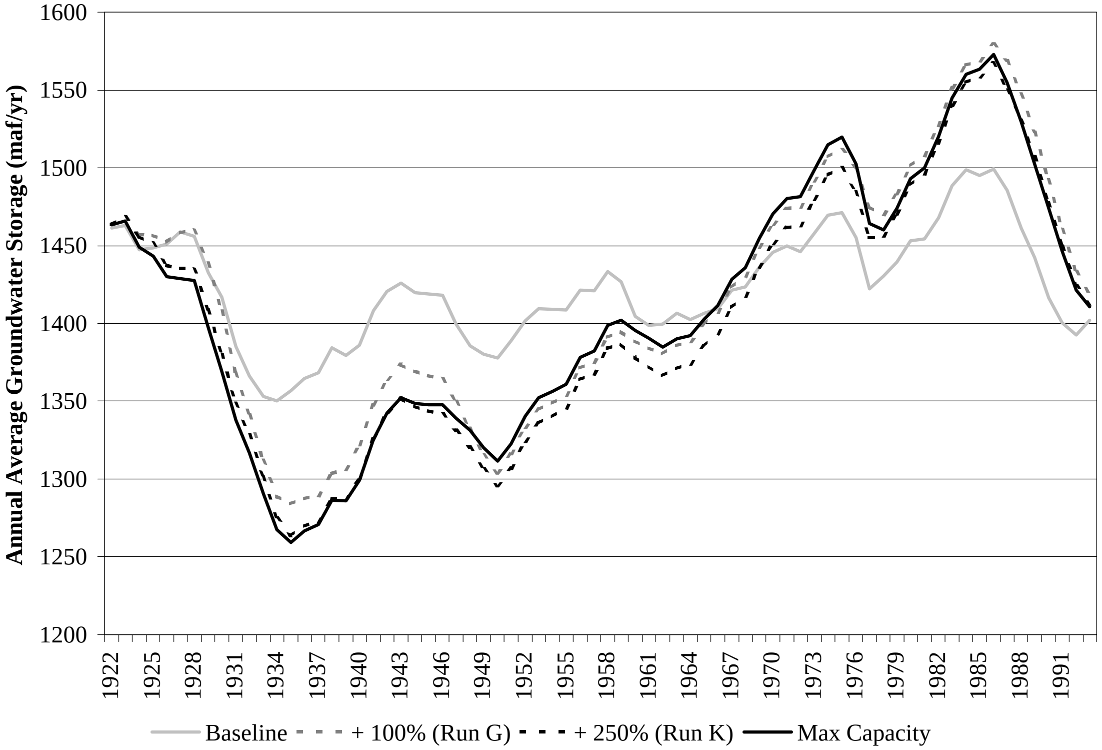

Figure 13: Annual Average Groundwater Storage (taf/yr)

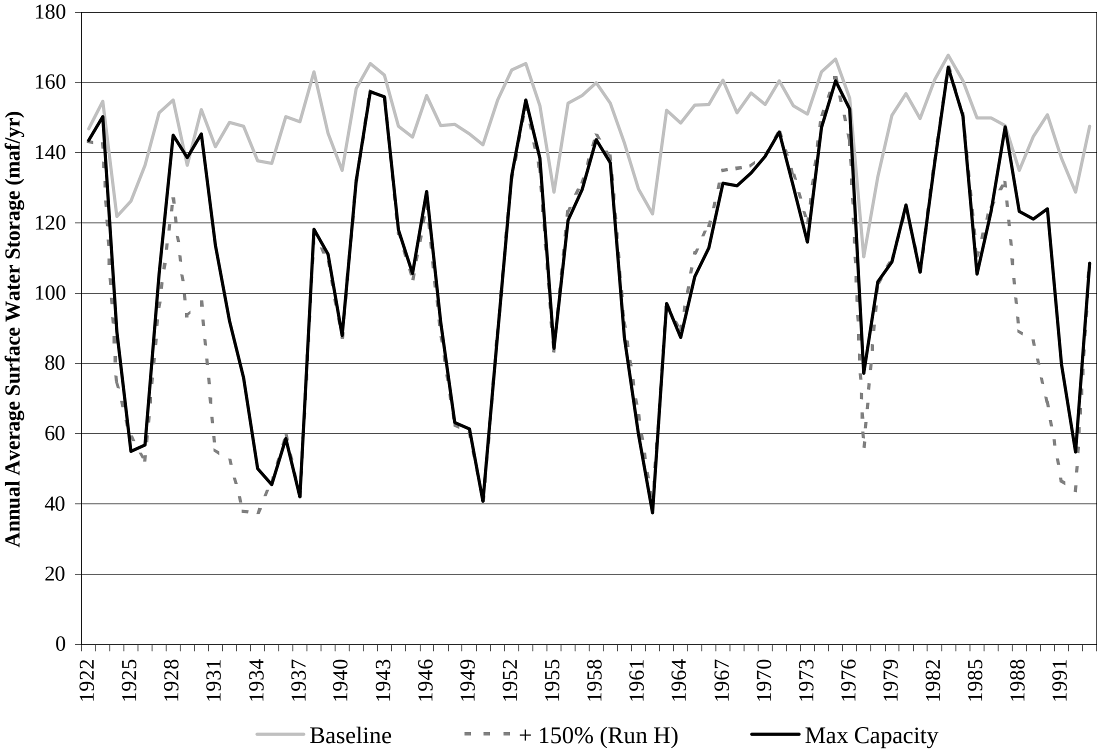

Figure 14: Annual Average Surface Water Storage (taf/yr)

The biggest change occurs in the surface water allocations. As the Delta Exports increase, agricultural users decrease surface water diversions, while urban users increase surface diversion. At the baseline exports, overall agricultural users obtain 56% of their demands from surface sources. However as exports increase that percentage drops to almost 40% (Figure 15). This is also true during the drought years, where agricultural users see an almost complete elimination of surface deliveries when exports exceed 10,100 taf/yr.

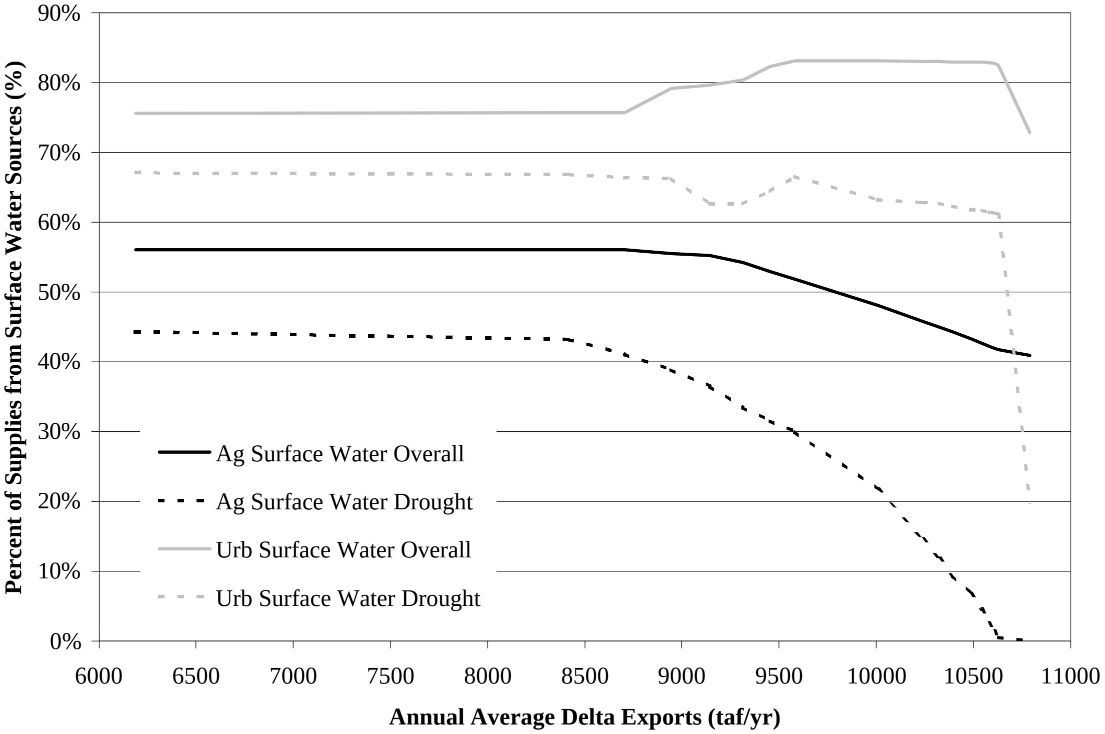

Figure 15: Percent of Supplies from Surface Sources (%)

Water Transfers and Exchanges

Water transfers with increasing Delta exports tend to be agricultural transfers to Delta Exports and transfers to support continued urban use. As exports increase, use of surface water for agriculture decreases, while urban surface water use increases. Agricultural users decrease their withdrawals from the Sacramento and American Rivers, while urban users increase. On the other hand, the urban users with access to groundwater reduce their withdrawals as exports increase while agricultural users increase pumping. See Figure 16.

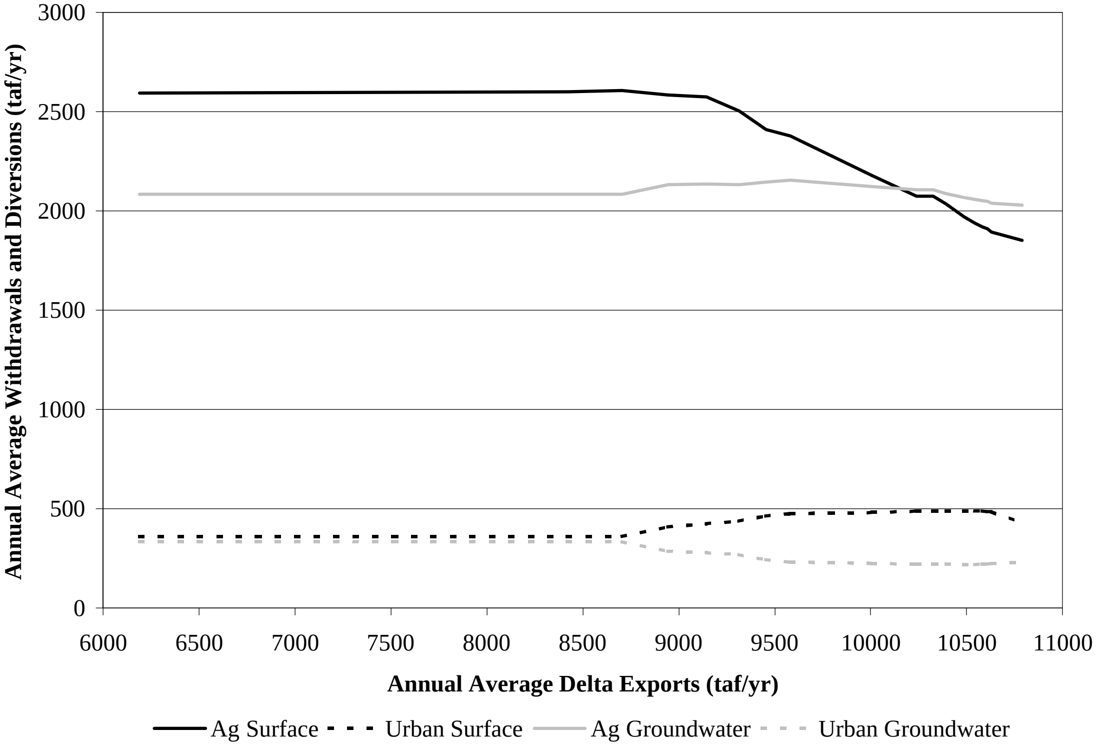

Figure 16: Surface and Groundwater Withdrawals (taf/yr)

Generally the agricultural users give up surface water to urban users, while urban users give up groundwater to agricultural users. With increasing Delta exports, the volume of deliveries lost by agriculture users greatly exceeds that of the urban users.

Effects of Carriage Water Requirements

As mentioned previously, the representation of the Delta water requirements are greatly simplified. When carriage water requirements were considered it increased the annual average export-related depletion to 12,285 taf/yr, including the carriage water. For Run R it was assumed that the carriage water requirement was 33% of the volume exported above baseline exports. Therefore, 10,274 taf/yr were exported and 2,011 taf/yr were required for carriage water purposes. Delta Exports were 516 taf/yr less than pumping plant capacity. At times, there was insufficient water in the system to meet carriage water requirements *and* pumping plant capacities.

The increase of 1,495 taf/yr of depletions over Run Q resulted in 673 taf/yr more agricultural and 326 taf/yr more urban water scarcity. The associated average scarcity costs were increased by $136M/yr for agriculture and $2,574M/yr for urban users. In general the carriage water requirement would increase scarcity and scarcity costs to the system. Increased scarcity and scarcity costs would be the likely outcome of any increased consumptive environmental water requirement.

Conclusions

Scarcity and Scarcity Costs are Unaffected Until Exports Exceed 9,144 taf/yr

Current levels of Delta Exports to the Central Valley and Southern California would not cause significant scarcities within the Sacramento Valley under an ideal market or other form of economically ideal water operations. At baseline exports, only one agricultural user experiences any scarcity. Delta exports could be increased by nearly 3,000 taf/yr without causing additional scarcities. This is primarily due to the relative abundance of water in the Sacramento Valley under current conditions.

Increased Costs of Delta Exports and 'Consumptive' Environmental Flows

As Delta Exports increase the marginal cost of exports and environmental flows ito Sacramento Valley users also increased. At baseline exports, the marginal costs of exports are less than $1/af. As exports increase, the marginal costs of exports also rose, reflecting the increased scarcity and scarcity costs. Increased exports may not initially affect the marginal costs on the environmental flows, but there are changes to the timing of surplus Delta outflows. The summer outflows are reduced as the exports increase, reducing water available to wildlife habitats during the critical summer months. In general, as the exports increase, the amount of water available to the environment decreases, with the remaining water having significant marginal costs.

Significant Value to Expansion of Some Facilities

Certain facilities would yield economic benefits if expanded, but primarily during drought periods. As exports increase, the value of facility expansion would also increase, especially for local recycling facilities to improve urban supply reliability. Additionally many of the proposed conveyance facilities would provide additional benefits to the system if constructed, especially if Delta Exports were increased.

Minimal Value to Expansion of Surface Water Reservoirs and Groundwater Basins

Most reservoirs (ground and surface water storage facilities) have little benefit to expansion, even with maximum exports. The marginal value to increasing groundwater storage capacity is always small. Surface storage facilities only have marginal values greater than $10/af/yr if exports were increased above 10,630 taf/yr. Thus, the greatest benefits to the Sacramento Valley would not come from expanding current storage facilities.

Benefits from an Ideal Water Market in the Sacramento Valley

Perhaps the greatest benefit to the Sacramento Valley would come from implementing economically ideal water operations. Current levels of Delta Exports combined with contractual agreement and legislative requirements result in significant scarcity and scarcity costs to both agricultural and urban users (Jenkins et al., 2001). The implementation of improved water operations reduces marginal costs within the region without having to change export levels.

Overall in the Sacramento Valley, if Delta Exports to the Southern Central Valley and Southern California were increased, agricultural users would face the majority of the scarcities. Agricultural opportunity cost would rise from $11.0/af at current export levels to $113.2/af at maximum exports. Urban users would see opportunity costs rise from $26.7/af to $1,048.1/af. However, urban users would not see significant impacts in their water deliveries until exports reached 10,300 taf/yr, which is approximately 67% over the current levels. In general, if freed to re-operate and re-allocate water in the Sacramento Valley, the region could export additional water without significant increases in scarcity and scarcity costs. However, there would be non-economic effects (such as reduced environmental flows) that may be significant and could limit any increase in Delta Exports.

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