In press, *Water Resources Research*

# Optimization of Environmental Water Purchases with Uncertainty

Sarah P. Hollinshead
Columbia University School of Law, Columbia University

Jay R. Lund
Department of Civil and Environmental Engineering, University of California, Davis

## ABSTRACT

Water managers are turning increasingly to market solutions to meet new environmental demands for water in fully allocated systems. This paper presents a three-stage probabilistic optimization model that identifies least-cost strategies for staged seasonal water purchases for an environmental water acquisition program given hydrologic, operational, and biological uncertainties. Multi-stage linear programming is used to minimize the expected cost of long-term, spot, and option water purchases used to meet uncertain environmental demands. Results prescribe the location, timing, and type of optimal water purchases and illustrate how least-cost strategies change as information becomes available during the year. Results also provide sensitivity analysis, including shadow values that estimate the expected cost of additional dedicated environmental water. The model's application to California's Environmental Water Account is presented with a discussion of its utility for planning and policy purposes. Model limitations and sensitivity analysis are discussed, as are operational and research recommendations.

## 1. INTRODUCTION

Scarcity of water tends to create conflicts between human and environmental uses. The Endangered Species Act (ESA) has greatly increased environmental demands with requirements for the protection and recovery of listed species. Water once used for irrigation, manufacturing, hydropower, and human consumption has been re-allocated to environmental uses in many locations (van Eeten and Roe 2002). Several efforts to meet ESA requirements, including minimum flows, have incorporated flexible, market-driven solutions (Anderson and Snyder 1997). In California the state and federal governments have entered the statewide water market on behalf of endangered fish, buying water to protect species and adaptively curtailing pumping from the San Francisco Bay/ Sacramento-San Joaquin Delta (the Delta) (Figure 1). Significant attention is now focused on how best to operate existing water supply systems and infrastructure to meet both human and environmental water demands.

Markets provide efficient means to move water from those who value it less to those for whom shortage is expensive (Vaux and Howitt 1984, Howe et al. 1986, Easter et al. 1998). Many western states have used markets to solve both temporary shortages due to droughts and long-term challenges of scarcity (Murphy et al. 2004). In some cases, public and private entities participate in markets on behalf of the environment, buying water rather than obtaining it through regulation or litigation. Such approaches avoid the cost, delay, and acrimony often associated with involuntary appropriation of the water by shifting the financial burden away from existing water users. This also promotes efficiency in the environmental use of the water, as buyers seek the greatest benefit to struggling fish species for their financial investment (Landry 1998b). The advent of environmental water purchases also has sparked interest in analytical planning tools that can provide an efficient and risk-free way to explore a wide array of water acquisition actions and opportunities for environmental water acquisition programs.

Between 1990 and 1997 agencies and environmental groups in 11 western states leased or purchased approximately 2.5 billion cubic meters of water for environmental uses (Landry 1998a). The threat of low stream flow to endangered fish motivated many of these transactions, as some of the U.S. Fish and Wildlife Service's biological opinions include water acquisitions, establishing legal requirements for protecting endangered species. In addition, major public purchase programs such as the Central Valley Project Improvement Act have increased the presence of public agencies and environmental interests in water markets to benefit wetlands and wildlife refuges as well as individual species. Interest groups such as the Nature Conservancy, Trout Unlimited, and local conservation organizations also have made substantial purchases to increase instream flows.

California faced the decision between litigation and use of markets to ease conflict in the 1990s as endangered fish in the Delta forced regulators to curtail pumping that provides much of the state's water supply. Agricultural and urban water contractors lost portions of their water supply without warning or compensation, resulting in significant political controversy and economic damage. The CALFED Bay-Delta Program (CALFED), a state and federal, multi-agency water management program, now addresses this conflict through its Environmental Water Account (EWA). The EWA provides water to compensate water contractors for fish-related reductions in water exported from the Delta, obtaining the compensatory water primarily through purchases on the statewide water market. California's EWA is similar to other public efforts to meet environmental water needs without placing the burden of those costs on private citizens or businesses. It offers one solution to "finding" water for the environment in a fully allocated system.

This paper presents a three-stage linear optimization model that identifies least-cost strategies for seasonal water purchases for programs such as California's EWA given probabilistic representations of hydrologic, operational, and biological uncertainties. Previous work has used deterministic optimization to examine the economic benefits of water markets in general (Brajer et al. 1989, Howe 1997) and in California (Jenkins et al. 2004). Two-stage linear programming has been used to maximize net economic benefits of water management plans and protection of endangered fish (Gillig et al. 2004) and to develop economically optimal market and conservation strategies for urban water supply (Lund and Israel 1995a). In addition, the Natural Heritage Institute sponsored a Monte Carlo model to optimize water purchases for the EWA (Electric Power Research Institute 2002).

The paper begins with a brief introduction to the Environmental Water Account and its role in California's water market. It then presents the mathematical formulation of the optimization model, its application to the EWA, and the associated results. Finally the paper addresses details of the results including sensitivity analysis and conclusions and recommendations for further study.

## 2. ENVIRONMENTAL WATER ACCOUNT

The San Francisco Bay/ Sacramento-San Joaquin Delta is the largest estuary on the West Coast of the United States, supporting over 500 species of plants and animals while simultaneously providing water for two thirds of California's residential and commercial users and over 3 million hectares of farmland (Hill 2001). To oversee such a complex and important resource, 25 state and federal agencies formed CALFED, an umbrella organization charged with improving both long-term ecological health and water operations in the Delta. The Environmental Water Account is CALFED's attempt to ensure that consumers receive their anticipated supplies of water and that Delta water exports do not harm threatened or endangered species of fish. The State Water Project and Central Valley Project (the Projects), the state's two largest water projects, draw up to 18.5 million $m^3$ (mcm) and 9.9 mcm per day from their respective pumping facilities at the southern end of the Delta (see Figure 1). In the past water users lost water supplies when regulators reduced pumping to protect fish. Water that went unpumped also went uncompensated, causing conflicts among water users, regulators, and environmental advocates.

### 2.1. EWA Structure and Operations

The Environmental Water Account is an arrangement between the U.S. Fish and Wildlife Service, NOAA Fisheries, California Department of Fish and Game (collectively the Management Agencies, which regulate the "take" or killing of endangered species), and the U.S. Bureau of Reclamation and California Department of Water Resources (the agencies that include the Projects and thus operate the export pumps). The EWA reduces export pumping by the Projects to protect fish (primarily winter and spring run Chinook salmon, Delta smelt, and steelhead trout) and it obtains water on the statewide market to reimburse the Projects for their forgone pumping. The timing and volume of these pumping reductions, or export cuts, varies with hydrology and fish behavior, making them difficult to predict in advance.

The EWA buys water through a combination of long-term, spot market, and option purchases. It also can adjust several of the water projects' operating procedures, such as increasing pumping during periods of high flow through the Delta, with the additional pumped water accruing to the EWA at no financial cost. The extra water collected through operational changes is known as the EWA's operational assets and its quantity varies with hydrologic conditions. California receives the vast majority of its precipitation between October and April, making for distinct seasons of accrual and then usage of water. This also creates noticeably seasonal patterns in both Project and EWA operations.

The EWA also has guaranteed access to 14.2 $m^3$/second (500 cfs) of pumping capacity during July and August. This is a right solely to conveyance, but it guarantees the EWA capacity to transfer at least 74 mcm of water from north to south across the Delta each summer. The Delta pumping plants form the only connection between northern California, where water is more abundant and less expensive, with southern California, where water is scarcer, with both higher demand and higher prices. Thus southern consumers have no access to northern sources of water unless they also have transfer capacity from north to south across the Delta. The EWA must repay the Projects in the south for export cuts, and so this transfer capacity is essential if the EWA is to use northern water acquisitions to cover its debts. Additional transfer capacity may be available to the EWA, especially in dry years. Transfers across the Delta are assessed a carriage water loss, which is the fraction of the transfer that must flow through the Delta and out to sea to maintain water quality or other regulated conditions. Carriage water losses vary with hydrology and project operations, but generally range from 0 to 25 percent.

2.2. California's Water Market

The EWA reduces Project pumping (exports) at key points in the biological and migratory cycles of several species of fish by as much as 430 mcm/year (CALFED Bay-Delta Authority 2003). It must procure enough water each year to cover the volume of its export cuts. The statewide water market in California, from which the EWA purchases most of its assets, encompasses several types of water transfers, three of the most common of which are long-term, spot market, and contingent transfers or option purchases (Lund and Israel 1995b, Howe 1997, Howitt 1998).

Long-term transfers offer both buyers and sellers a predictable quantity and price of sale, insulating the transactions from the often-volatile effects of weather and hydrology on annual and seasonal water prices and availability. These transfers often have lower prices, as the seller benefits from the ability to plan crops or other affected resources with knowledge of the sale. Long-term contracts also can be tied to a pre-designated set of conditions such that they are executed only in dry years or other designated events. In some markets the priority of a water right or contract will affect its market price, as senior rights provide more reliable water supplies in dry years when not all right holders receive water. To date, the EWA has made some beginning-of-year purchases that have many of the advantages of long-term contracts because they are made before hydrologic conditions and other variables are known. However, it has not yet used long-term contracts.

Spot market transfers offer flexible, short-term opportunities for buyers to meet immediate needs without previous arrangements. Spot market prices vary substantially in response to hydrology (e.g., the availability of water), location, water quality, and storage arrangements. Prices tend to increase in dry years and also increase later in the year as agricultural sellers have already planted crops that will be reduced or lost if water is sold. Prices in California are substantially higher south of the Delta where local water is scarcer and demand for water is greater. The EWA has made extensive use of spot market purchases, most recently to supplement other types of purchases.

Contingent transfers, or options, offer buyers the opportunity to guarantee the availability and price of water before their needs are known. Options include two components: a fixed price guarantees access to the water and a strike price covers the cost of exercising the option and taking delivery of the water. Strike prices tend to increase with later call dates, as agricultural sellers must decide whether to plant crops that will use the optioned water or leave fields fallow if the buyer exercises the options. However, the total cost of optioned water (i.e., the option price plus the strike price) is often lower than an equivalent spot market purchase as the seller is guaranteed a minimum sale price for the option contracts and retains the possibility of using the water if the options go unexercised (Howitt 1998). Option contracts are signed early in the year before information on weather or hydrology (or export cuts) is available, and so they offer some protection against the volatility of spot prices. The EWA has made increasing use of options, which provide both guaranteed prices and flexibility to address the variability and uncertainty of export cut requirements. While options include a risk of paying contractual costs in years when they remain unexercised, this cost is small relative to the total price and present an attractive alternative to high exposure to spot prices in dry years.

The EWA executes these transactions with water districts, groundwater banks, and other major sellers in California's water market. Like other large purchasers, the EWA buys from water districts, rather than from individuals, as individual water users often are constrained to sell their water either within or back to their own water district, making direct sales to buyers such as the EWA less likely. Experience to date indicates (and this model assumes) that the EWA is a price taker on the statewide market, despite the size of its purchases. Between 2001 and 2004, the EWA averaged less than 300 mcm in total annual purchases, which is 20 percent of the statewide market's average of 1,500 mcm in annual purchases during the same period (CALFED Bay-Delta Authority 2005, Hanak 2005). However, few water markets are as large, diversified, and well developed as California's. In other situations a large environmental buyer might dwarf other purchasers and thus have more influence over water's market price.

## 3. MODEL FORMULATION

This optimization model suggests least-cost decisions for managers who must purchase water in a fully allocated system for environmental purposes such as California's EWA. It does not address the full physical or economic complexity of California's water system or the entire water market. It represents a single large buyer addressing a single, uncertain demand (export cuts) that it must meet in full. It does not consider subtleties such as the priority of the water it buys, but instead assumes that all purchases are of stored water or senior water rights whose delivery is guaranteed (this reflects the EWA's actual experience in California's water market). The formulation also neglects any explicit relationship between the quantity of water purchased and its unit price. However, in the model, the unit price decreases and the total volume of export cuts increases with wetter hydrologic conditions. As data become available, explicit quantity effects on price can be added to this formulation as a piece-wise linear function.

Managers purchase different types of water contracts at different times of year. The model uses long-term, option, and spot market purchases as well as operational assets to meet demands. Hydrologic conditions ($H_h$), availability of operational assets ($W_{hi}$) and transfer capacity ($Tcap_{hj}$), and volume of export cuts ($E_{hk}$) are all unknown at the beginning of the year and are thus expressed as probabilistic random variables. Quantities of operational assets, transfer capacity, and export cuts all depend on hydrology, $h$, with $H_1$ representing very dry conditions and $H_5$ being very wet. This model examines all possible combinations of the four random variables simultaneously. Each random variable is discretized into $m$ different values, and so we evaluate $m^4$ combinations of events, each with its own joint probability, in a staged decision process with recourse. The final, optimal decision strategy minimizes the overall expected value or average cost considering every scenario (Hollinshead 2005).

The water year is divided into three stages: (1) October through January, when little is known about any of the variables described above, (2) February through April, when hydrologic conditions become clear and the EWA collects operational assets, and (3) May through September when all conditions, including hydrology, operational opportunities, transfer capacity, and export cuts become known. The model represents purchases of long-term ($P_y$) and option ($OP_y$) water contracts (at different locations $y$, north and south of the Delta) as first stage decisions, as both decisions often predate the availability of season-specific hydrologic and operational information. As the year progresses and more information becomes available in the second and third stages, managers can choose to purchase more water at higher spot market prices ($SP_{2yhi}$ or $SP_{3yhijk}$) or exercise options ($EO_{2yhi}$ and $EO_{3yhijk}$) for the locations and conditions described by the subscripts. Doing so costs less in the second stage than the third. All cost and carriage water parameters are known in all stages. The problem is presented as an explicitly stochastic three-stage linear program whose decisions and known and unknown conditions are summarized in Table 1. This integrates all decisions and probabilistic scenarios into a decision-theoretic framework, which is solved simultaneously and considers the recourses available at each stage to minimize the average annual cost (Loucks et al. 1981).

The model's objective function (Equation 1) minimizes the average cost of EWA water purchases over one year of operation. Constraints require that the EWA procure enough water to cover export cuts (Equation 2); prevent exercising more options than purchased in the first stage, both north and south of the Delta (Equation 3); prevent transfers from exceeding either water purchased north of the Delta (Equation 4) or available cross-Delta transfer capacity (Equation 5); and ensure that the only decision variable that can take a negative value is $S_{yhijk}$, or storage (Equation 6). Negative storage represents debt that the EWA owes to the Projects; for now, all storage (debt) is set to zero ($S_{yhijk} = 0$).

The resulting linear problem is

$$\text{Min } Z = \sum_{y}\Bigg\{c_{1yP}P_y + c_{1yOP}OP_y + \sum_{h=1}^{m}\sum_{i=1}^{m} p_h * p_{hi} * \Big[c_{2ySPh}SP_{2yhi} + c_{2yEOh}EO_{2yhi} + \sum_{j=1}^{m}\sum_{k=1}^{m} p_{hj} * p_{hk} * \left(c_{3ySPh}SP_{3yhijk} + c_{3yEOh}EO_{3yhijk}\right)\Big]\Bigg\} \quad (1)$$

Subject to

Demand constraint

$$P_{SOD} + SP_{2SODhi} + EO_{2SODhi} + SP_{3SODhijk} + EO_{3SODhijk} - S_{SODhijk} + W_{hi} + T_{hijk} \geq E_{hk} \quad \forall\ h,i,j,k \quad (2)$$

Option use constraint

$$EO_{2yhi} + EO_{3yhijk} \leq OP_y \ \forall \ \ y,h,i,j,k \quad (3)$$

Transfer quantity constraint

$$(1-\alpha_h)*\left(P_{NOD} + SP_{2NODhi} + EO_{2NODhi} + SP_{3NODhijk} + EO_{3NODhijk} - S_{NODhijk}\right) \geq T_{hijk} \quad \forall\ h,i,j,k \quad (4)$$

Transfer capacity constraint

$$T_{hijk} \leq Tcap_{hj} \quad \forall\ h, i, j, k \quad (5)$$

$$P_y;\ OP_y;\ SP_{2yhi};\ SP_{3yhijk};\ EO_{2yhi};\ EO_{3yhijk};\ T_{hijk} \geq 0 \quad \forall\ y, h, i, j, k \quad (6)$$

Where model decision variables are

| | |
|---|---|
| $EO_{2yhi}$ | second stage options exercised at location $y$ in hydrologic event $h$ given operational assets $i$ in thousands of cubic meters (tcm); |
| $EO_{3yhijk}$ | third stage options exercised at location $y$ in hydrologic event $h$ given operational assets $i$, transfer capacity $j$, and export cuts $k$ (tcm); |
| $OP_y$ | option contracts purchased in the first stage at location $y$ (tcm); |
| $P_y$ | water purchased with long-term agreements at location $y$ (tcm); |
| $SP_{2yhi}$ | second stage spot market purchases at location $y$ in hydrologic event $h$ given operational assets $i$ (tcm); |
| $SP_{3yhijk}$ | third stage spot market purchases at location $y$ in hydrologic event $h$ given operational assets $i$, transfer capacity $j$, and export cuts $k$ (tcm); |
| $S_{yhijk}$ | carryover storage at the end of the third stage at location $y$ in hydrologic event $h$ given operational assets $i$, transfer capacity $j$, and export cuts $k$ (tcm), which appears only in the constraints and is not maximized or minimized, but rather provides slack on the demand and transfer constraints [equations (2) and (4)]; |
| $T_{hijk}$ | water transferred across the Delta in hydrologic event $h$ given operational assets $i$, transfer capacity $j$, and export cuts $k$ (tcm), which appears only in constraints, linking the north of Delta and south of Delta decisions; |

and the model parameters are

| | |
|---|---|
| $c_{1yz}$ | unit price at location $y$ of first stage purchase type $z$ ($/tcm); |
| $c_{xyzh}$ | unit price in stage $x$ at location $y$ of purchase type $z$ in hydrologic event $h$ ($/tcm); |
| $E_{hk}$ | export cuts in event $k$ given hydrologic event $h$ (tcm); |
| $H_h$ | hydrologic event in year type $h$ with $H_1$ being very dry and $H_5$ very wet; |
| $p_h$, $p_{hi}$, $p_{hj}$, $p_{hk}$ | probability of the subscripted event; |
| $Tcap_{hj}$ | available cross-Delta transfer capacity in event $j$ given hydrologic event $h$ (tcm); |
| $W_{hi}$ | operational assets in event $i$ given hydrologic event $h$ (tcm); |
| $\alpha_h$ | carriage water loss across the Delta in hydrologic event $h$; |

where the indexes on subscripts are

| | |
|---|---|
| $x$ | model stage number |
| $y$ | location, north of Delta (NOD) or south of Delta (SOD) |
| $z$ | water purchase type |
| $h$ | index of hydrologic events |
| $i$ | index of operational assets available for each hydrologic event $h$ |
| $j$ | index of transfer capacity available for each hydrologic event $h$ |
| $k$ | index of export cuts for each hydrologic event $h$ |
| $m$ | number of increments in each range of random variables. |

The probability distributions for each random variable in this application are discretized into $m = 5$ distinct values, resulting in $m^4$ or 625 distinct scenarios. More detailed representation of each random variable may be unnecessary and even disadvantageous for a management screening tool as more scenarios alone do not necessarily provide better or clearer suggestions of optimal strategy and require increasing time and effort for computation, parameter estimation, and interpretation of voluminous output. This model is designed for use by managers who make water purchase decisions with incomplete information, and so increasing detail may provide few benefits. This optimization model is solved in GAMS and post processed using Excel (Brooke et al. 1998).

## 4. APPLICATION

Results suggest a least-cost staged decision strategy for the location, timing, and types of water purchase quantities to meet environmentally required export cuts. This optimal staged decision strategy minimizes average purchase cost over all uncertain scenarios. While the cost of decisions might exceed that required for a single, specific scenario, the strategy provided by the model minimizes the average of all costs over all possible combinations of conditions.

### 4.1. Model Inputs

Model inputs include probability distributions for hydrologic events, operational assets, transfer capacity, and export cuts as well as cost and carriage water parameters. The probabilities and quantities of operational assets, transfer capacity, and export cuts all vary with hydrologic year type. The results presented here are based on inputs provided by Project staff, which reflect recent conditions and events in California. These inputs could be modified to reflect other conditions, such as those associated with climate change or new water management policies. Figure 2 provides the probability distributions for all random variables. Table 2 contains cost coefficients for purchases of water and options north and south of the Delta, which vary with the model stage and hydrologic year type. Carriage water losses are held constant at 15 percent for this application.

### 4.2. Cost Results

This model produces a variety of cost results, the simplest of which is the average cost for a single year of operation over all scenarios (here $38.6 million, with individual scenario costs ranging from $11.0 to $82.7 million). Perhaps of greater use to managers, Figure 3 shows the probability of each total cost, overall and for each of five hydrologic conditions (year types). In this example, the moderately wet conditions of the $H_4$ hydrology result in significantly higher costs than other scenarios because the EWA tends to make its largest export cuts in moderately wet conditions when transfer capacity limits access to inexpensive northern water.

As additional information becomes available during the year, the probability of specific costs and remaining optimal decisions changes for the remainder of that year. For example, the average cost for all scenarios is $38.6 million, whereas the average for a moderately dry year ($H_2$) is $32.4 million (ranging from $11.0 to $80.5 million) and that given the moderately dry year and moderately low operational assets ($H_2$ and $W_2$) is $36.2 million (ranging from $25.0 to $41.9 million). As additional information becomes available (as the year progresses), the expected value cost approaches a scenario-specific cost at the end of the year when all uncertainties are resolved.

### 4.3. Least-Cost Decisions

Purchase decisions occur in staged sequence, with increasing amounts of information as the year progresses. Within a purchase strategy, managers make long-term purchases based on conditions they anticipate in most years. As each operational season progresses, they refine estimates of export cuts, consider acquisitions for that year to date, and plan additional purchases accordingly. This model similarly provides optimal first stage decisions for long-term and option contract purchases that are the same for all conditions, as well as decisions customized to each subsequent stage given decisions already made in the previous stage(s). Figure 4 shows the average quantity of optimal acquisitions, by hydrologic event, model stage, and purchase type. While these averages lump many possible combinations of decisions, they demonstrate how purchase strategies change with hydrologic events, which is useful for planning purposes.

Figure 4 shows combined optimal long-term (first stage) purchases (87.1 mcm north of the Delta and 36.1 mcm in the south) that are less than the smallest anticipated quantity of export cuts in a single year, reflecting the decision to lock in a minimum baseline of less expensive water. First stage decisions also include 43.5 mcm of option contracts north of the Delta and 40.5 mcm in the south. These more flexible and slightly more expensive (if exercised) purchases reflect expected expenditures, which exceed the very lowest level of export cuts when combined with the long-term purchases. The lower quantities of south of Delta purchases reflect an unwillingness to commit to relatively expensive water that might go unused. Such stranded assets are rare, as total optimal purchases (less carriage water losses) exceed export cuts in less than six percent of all scenarios. It is far more common and less costly to leave un-needed options unexercised, demonstrating the cautious nature of first stage commitments. In reality, managers would store excess water that this model currently considers unused, untransferred, and without value in Project reservoirs or groundwater banks for use in subsequent years. Additional flexibility from using or allowing storage in the model should reduce average costs and make lower-cost long-term purchases more attractive.

Second stage decisions reflect both first stage commitments and the remaining third-stage uncertainties regarding transfer capacity and export cuts. Exercising options or making spot purchases north of the Delta in this stage is only optimal in drier hydrologic events when lower quantities of operational assets are available. While the availability of transfer capacity is unknown in the second stage, its strong tendency to increase with dryer hydrologic events leads to the recommendation to exercise options or make spot purchases in the (less expensive) second stage only when conditions are dry and chances of successful transfer are high. In contrast, it is usually optimal to exercise second stage options in the south, mostly in wet years and especially when operational assets are low. Sharp drops in water prices cause much of this wet year activity. The quantity of options exercised is limited by the first stage decision to purchase only 40.5 mcm of option contracts. However, spot purchases have no such limits and so while they occur slightly less frequently (in 60 percent of all years), second stage spot purchases can approach 222 mcm in the south. These larger purchases occur in moderately wet ($H_4$) years when operational assets are low. Under these conditions, transfer capacity is likely to be low (precluding significant purchases north of the Delta) and export cuts are likely to be high. Under no circumstances is it optimal to simultaneously make spot purchases or exercise options both north and south of the Delta in the second stage.

Third stage (recourse) decisions vary widely, reflecting full information on all formerly random variables as well as first and second stage commitments. Third stage decisions always represent least-cost efforts to meet outstanding demand, and so they are greatest when export cuts are greatest.

Both the first stage decision regarding option purchase quantities and any second stage decisions to exercise options limit the exercise of options in the third stage. These influences mean that quantities of options exercised in the third stage reflect remaining opportunities, such as exercising north of the Delta options in average ($H_3$) hydrologic events, taking advantage of instances when transfer capacity is available. Over all hydrologic events, it is less common to exercise third stage options south of the Delta than north because so many options already were exercised in the south during the second stage (and so few options remain). Third stage spot purchases represent the relatively expensive solution when managers have exhausted all other available sources of less expensive water. Third stage spot purchases tend to be large north of the Delta in dry years when transfer capacity is available to move water south, and the frequency and magnitude of purchases decrease with increasingly wet hydrologic events. South of Delta third stage spot purchases show the opposite pattern; they are optimal in 95 percent of wetter ($H_4$ and $H_5$) years, with maximum purchases of 284 mcm. Third stage spot purchases are optimal south of the Delta in less than 40 percent of moderately dry ($H_2$) years and only 14 percent of dry ($H_1$) years. The large differences in the distribution of spot purchases by location across hydrologic events are caused primarily by wide differences in south of Delta water prices and cross-Delta transfer capacities across hydrologic events. Because third stage spot purchases south of the Delta are almost \$100/tcm more expensive in dry years than in wet, the purchase strategies for those years are very different.

## 5. SENSITIVITY ANALYSIS

The sensitivity analysis provided by standard linear optimization software can be useful in evaluating how sensitive results are to uncertainties in each input (Hillier and Lieberman 2001). Linear optimization provides shadow values (Lagrange multipliers) or range-of-basis information for every cost coefficient and constraint in a model, indicating areas in which increased flexibility or changes in costs would have the greatest effect on average costs. This model provides reduced price coefficients, which are the amount by which unit prices for water would have to decrease before a particular purchase would become optimal for a given combined event scenario. This is the reduced cost, corrected for the probability associated with each specific scenario (Hollinshead 2005).

The highest reduced price coefficients for third stage spot purchases equal the next lowest price for water that the model did not buy (e.g., the full price of an additional unit of water). These occur when first and second stage decisions are sufficient to cover export cuts, making further third stage purchases superfluous. In these cases, spot purchases would have to be costless to enter the optimal solution. Reduced price coefficients equal zero when third stage spot purchases are already optimal given their current cost coefficients. Reduced price coefficients generally are lower for second stage spot purchases, never reaching the full value of the cost coefficient itself. This happens because no instances exist when previous (here, first stage) decisions have completely covered export cuts for all possible remaining scenarios, and so any second stage decision could become optimal if its price was low enough. Similar reduced price coefficient information is available for exercising options and other purchase types.

Shadow values for model constraints represent the change to the objective function (here, the average total cost) that will result from loosening a constraint by a single unit. When corrected for the probability associated with each possible combination of events, this indicates how much relaxing a constraint by one unit would reduce the overall cost of a specific scenario. The highest shadow values occur on constraints requiring water acquisitions to cover export requirements and those limiting cross-Delta transfers to the specified transfer capacity [Equations (2) and (5)]. In each case, shadow values reach $203/tcm, which is the full price of the most expensive purchase required to satisfy the constraint. Averaged over all scenarios, these shadow values are $119/tcm for export cuts and $57/tcm for transfer capacity. These shadow values are useful as EWA managers evaluate the important constraints in the system where changes could provide the greatest savings. The full range of shadow values for the demand (export cuts) can tell managers how much the last unit of a requirement costs and can suggest how often the requirement is more or less expensive. For example, Figure 5 shows that additional export cuts would cost $119/tcm or less in half of all scenarios, but in average ($H_3$) hydrologic conditions, they will cost $162/tcm in 80 percent of all scenarios.

The most flexible form of sensitivity analysis provided by any model is the comparison of model outputs for different sets of inputs. Since this model runs quickly, such analyses are easy, allowing modelers to examine the response of the entire set of modeled conditions to changes in multiple inputs. For example, reducing export cut quantities by 50 mcm across all conditions reduces the average total cost by $6.5 million, or 16.8 percent, to $32.1 million per year. This type of information could be particularly useful to EWA managers as they consider how to make export cuts within limited financial budgets.

## 6. MODEL LIMITATIONS

All models are simplifications of reality. Here, we assume that all parameter values are known, including water prices that vary with market conditions during the operating year. While this is a simplification, use of expected cost coefficients is sufficient for expected value decision making (Wagner 1975). Carriage water losses are also unpredictable, depending on a complex set of conditions that affect the state of the Delta at any point in time. These parameter values could be updated as more information becomes available.

Perhaps the model's single greatest limitation is its current exclusion of carryover storage and debt. This formulation does not provide a value for storage, whereas managers can store any water left at the end of the operating year, offsetting some cost of purchases in future years. The EWA also can go into debt to the Projects on the condition that it repays debt in the following year in addition to covering that year's export cuts. Amassing large debt carries risks to the next year's operations, but it also provides an attractive alternative to making expensive third stage spot purchases when export cuts exceed expectations. Finally, this model minimizes the average cost of purchases under the assumption that it must meet all demands. While the EWA is expected to make sufficient export cuts to protect endangered species of fish, budgetary considerations are likely to influence the quantity of export cuts and water purchases in any given operating season. The current formulation is useful for examining the costs associated with the range of export cuts that the EWA is likely to encounter. It also suggests economically efficient purchase strategies for many different combinations of events, but it does not reflect the full decision making process for EWA managers.

## 7. CONCLUSIONS AND RECOMMENDATIONS

Models such as this provide an efficient and risk-free means for environmental water managers to logically structure and explore a wide array of acquisition options and strategies. Water districts and other large water purchasers can also employ such optimization models to develop their own water purchase strategies. As agencies explore new approaches to providing water for environmental protection, modeling tools that permit experimentation at little financial or biological cost are essential. While no model can capture the full complexity of California's hydrology, project operations, and water market, this model formulation provides EWA managers with both an exploratory tool and a foundation for further model developments. It also provides an analytical primer for water managers in other locations who face similar conflicts between water reliability and fishery protection.

Computer models offer low risk, low cost tools for exploring alternative and potentially promising strategies for operating a complex water market portfolio such as the EWA. Probabilistic optimization models can explore a far wider and more complex range of alternatives and uncertainties than would be possible with traditional simulation models alone. Applications can focus on new approaches to purchasing strategy, including adjusting purchase locations, timing, and type. Applications also can investigate how least-cost strategies change with our understanding of hydrologic, operational, biological, and cost inputs. Decisions that are robustly optimal over a wide range of conditions may warrant more emphasis in policy, planning, and operational decisions.

With the current model application, water year type is the single best predictor of EWA costs, as it affects the market price of water, availability of operational assets and cross-Delta transfer capacity, and quantity of export cuts. Operational assets and export cuts affect the total cost of operations, but strategic decisions of where (north or south of Delta) and when (first, second, or third stage) to acquire water on an annual basis depend primarily on cross-Delta transfer capacity. The sharp decrease in south of Delta water prices in wetter ($H_4$ and $H_5$) years mitigates the effects of hydrology on transfer capacity and access to north of Delta markets. However, moderately wet years still have the highest expected costs as they experience the highest export cuts with only somewhat decreased water prices. As is often true in water management, greater flexibility reduces costs of operations. Access to cross-Delta transfer capacity is the strongest example of this, as it determines the location, and by extension the cost of most water purchases. As a result, increasing access to this transfer capacity will reduce average costs, especially in wet years. Access to storage and debt also will reduce average costs from those estimated here and make lower-cost long-term purchases more attractive for EWA operations, as each provides managers with additional, lower-cost tools to address demands that fall at either the very low or very high end of the range for all export cuts.

This paper provides the basic formulation for a probabilistic optimization model that can be used directly or modified to address additional questions regarding EWA operations. Developments that are likely to provide the greatest further insight to managers and others interested in similar programs include reformulating the linear program to minimize water deficits (i.e., the difference between purchases and export cuts) within a specified, perhaps probabilistic, financial budget. Developing appropriate values, limits, and costs for storage to reflect the EWA's use of storage and debt also would make model results more realistic. The addition of a large water bank to balance surpluses and debt over a range of events, perhaps at some cost, would provide the EWA with a tool to buffer the extreme lows and highs of export cuts.

This model formulation illustrates the value of modeling and economic-engineering optimization tools to policymakers. As market-based solutions like the EWA are applied to conflicts between water supply and environmental uses in other locations, optimization tools can help market-based environmental programs develop their own purchase strategies. The results of this specific model demonstrate how environmental water purchasing strategies should respond to hydrologic, operational, economic, and biological influences.

**ACKNOWLEDGEMENTS**

The authors thank Curtis Spencer for his assistance with model inputs and ongoing model development, David Fullerton for his comments on earlier versions of this work, and two anonymous reviewers, the Associate Editor, and Editor for useful suggestions. This material is based upon work supported under a National Science Foundation Graduate Research Fellowship.

**REFERENCES**

Anderson, T. L., and P. S. Snyder (1997), *Water Markets: Priming the Invisible Pump*, Cato Institute, Washington, DC.

Brajer, V., A. Church, R. Cummings, and P. Farah (1989), The Strengths and Weaknesses of Water Markets as They Affect Water Scarcity and Sovereignty Interests in the West, *Natural Resources Journal, 29*, 489-510.

Brooke, A., D. Kendrick, A. Meeraus, and R. Raman (1998), *GAMS: A User's Guide*, GAMS Development Corporation, Washington, D.C.

Brown, R., and Kimmerer, W. (2001), Delta Smelt and CALFED's Environmental Water Account, CALFED Science Program, Sacramento, CA.

CALFED Bay-Delta Authority (2005), Environmental Water Account Acquisition Strategy for 2005, Sacramento, CA.

CALFED Bay-Delta Authority (2003), WY 2002/2003 EWA Accounting Summary, Sacramento, CA.

Easter, K. W., M. W. Rosengrant, and A. Dinar, editors (1998), *Markets for Water: Potential and Performance*, Kluwer Academic Publishers, Norwell, MA.

Electric Power Research Institute (2002), *Got Water? Developing an Optimal Asset Purchasing Strategy for the CALFED Environmental Water Account*, Natural Heritage Institute, Berkeley, CA.

Gillig, D., B. A. McCarl, L. L. Jones, and F. Boadu (2004), Economic Efficiency and Cost Implications of Habitat Conservation: An Example in the Context of the Edwards Aquifer Region, *Water Resources Research, 40*(4), W04102, doi:04110.01029/02003WR002749.

Hanak, E. (2005), *Water for Growth: California's New Frontier,* Public Policy Institute of California, San Francisco, CA.

Hill, E. G. (2001), Environmental Water Account: Need for Legislative Definition and Oversight, Legislative Analyst's Office, Sacramento, CA.

Hillier, F. S., and G. J. Lieberman (2001), *Introduction to Operations Research*, 7th edition, McGraw-Hill, New York, NY.

Hollinshead, S. (2005), Optimization of Environmental Water Account Purchases with Uncertainty, M.S., University of California, Davis, Davis, CA.

Howe, C. W. (1997), Increasing Efficiency in Water Markets: Examples form the Western United States, in *Water Marketing: the Next Generation*, edited by T. L. Anderson and P. J. Hill, Rowman and Littlefield Publishers, Boulder, CO.

Howe, C. W., D. R. Schurmeir, and W. D. Shaw (1986), Innovative Approaches to Water Allocation: The Potential for Water Markets, *Water Resources Research, 22*(4), 439-445.

Howitt, R. E. (1998), Spot Prices, Options Prices, and Water Markets: An Analysis of Emerging Markets in California, in *Markets for Water: Potential and Performance*, edited by K. W. Easter, M. W. Rosegrant, and A. Dinar, Kluwer Academic Publishers, Boston, MA.

Jenkins, M. W., J. R. Lund, R. E. Howitt, A. J. Draper, S. M. Msangi, S. K. Tanaka, R. S. Ritzema, and G. F. Marques (2004), Optimization of California's Water Supply System: Results and Insights, *Journal of Water Resources Planning and Management, 130*(4), 271-280.

Landry, C. (1998a), Market Transfers of Water for Environmental Protection in the Western United States, *Water Policy, 1*, 457-469.

Landry, C. J. (1998b), Saving Our Streams Through Water Markets, Political Economy Research Center, Bozeman, MT.

Loucks, D. P., J. R. Stedinger, and D. A. Heith (1981), *Water Resources Systems Planning and Analysis*, Prentice-Hall, Englewood Cliffs, NJ.

Lund, J. R., and M. Israel (1995a), Optimization of Transfers in Urban Water Supply Planning, *Journal of Water Resources Planning and Management, 121*(1), 41-48.

Lund, J. R., and M. Israel (1995b), Water Transfers in Water Resource Systems, *Journal of Water Resources Planning and Management, 121*(2), 193-204.

Murphy, J. J., A. Dinar, R. E. Howitt, S. J. Rassenti, V. L. Smith, and M. Weinberg (2004), Incorporating Instream Flow Values into a Water Market, Working Paper University of Massachusetts, Amherst, Amherst, MA.

van Eeten, M., and E. Roe (2002), *Ecology, Engineering and Management: Reconciling Ecosystem Rehabilitation and Service Reliability*, Oxford University Press, Oxford.

Vaux, H. J., and R. E. Howitt (1984), Managing Water Scarcity: An Evaluation of Interregional Transfers, *Water Resources Research, 20*, 785-792.

Wagner, H. M. (1975), *Principles of Operations Research*, Prentice-Hall, Englewood Cliffs, NJ.

**FIGURE CAPTIONS**

Figure 1: Map of the San Francisco Bay/ Sacramento-San Joaquin Delta

Figure 2: Probability Distributions for Model Inputs

Figure 3: Total Costs, by Hydrologic Event

Figure 4: Average Water Acquisitions, by Hydrologic Event and Purchase Type

Figure 5: Probability-Corrected Shadow Values for Export Cut Requirements by Hydrologic Event

| Table 1: Decision Stages, Decisions, and Known and Unknown Conditions | | | |
|---|---|---|---|
| Stage | 1 | 2 | 3 |
| Time | October – January | February – April | May – September |
| Decisions | $P_y$, $OP_y$ | $SP_{2yhi}$, $EO_{2yhi}$ | $SP_{3yhijk}$, $EO_{3yhijk}$, $T_{hijk}$, $S_{yhijk}$ |
| Known conditions | Unit costs and probabilities | Stage 1 decisions, $H_h$, $W_{hi}$, $\alpha_h$ | All |
| Unknown conditions | $H_h$, $W_{hi}$, $\alpha_h$, $Tcap_{hj}$, $E_{hk}$ | $Tcap_{hj}$, $E_{hk}$ | None |

| Table 2: Cost Coefficients for Decision Variables by Model Stage, Hydrologic Event, Purchase Type, and Location ($/tcm) | | | | | |
|---|---|---|---|---|---|
| Stage | | $P_{NOD}$ | $P_{SOD}$ | $OP_{NOD}$ | $OP_{SOD}$ |
| 1 | | 61 | 130 | 8 | 16 |
| Stage | Hydrologic Event | $SP_{NOD}$ | $SP_{SOD}$ | $EO_{NOD}$ | $EO_{SOD}$ |
| 2 | $H_1$ | 93 | 186 | 69 | 170 |
| | $H_2$ | 81 | 178 | 65 | 162 |
| | $H_3$ | 73 | 154 | 57 | 130 |
| | $H_4$ | 61 | 134 | 49 | 113 |
| | $H_5$ | 57 | 109 | 45 | 89 |
| 3 | $H_1$ | 101 | 203 | 77 | 178 |
| | $H_2$ | 89 | 195 | 73 | 170 |
| | $H_3$ | 81 | 162 | 65 | 138 |
| | $H_4$ | 69 | 138 | 57 | 122 |
| | $H_5$ | 65 | 113 | 53 | 97 |

Figure 1: Map of the San Francisco Bay/ Sacramento-San Joaquin Delta

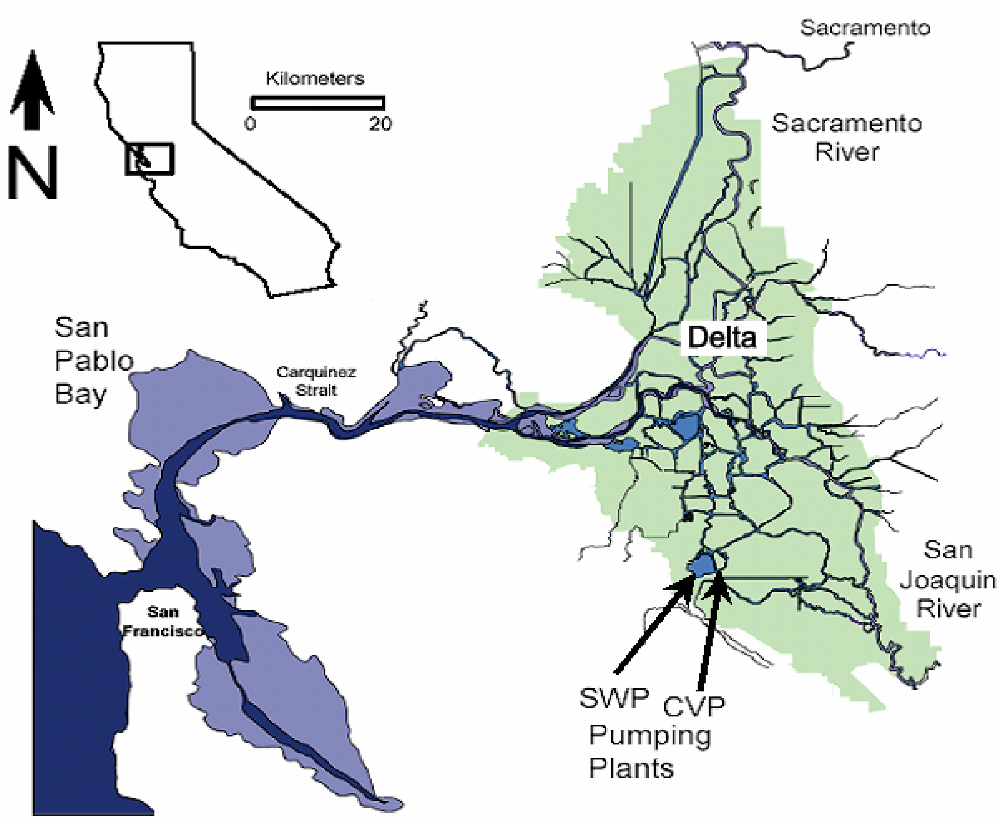


Figure 2: Probability Distributions for Model Inputs

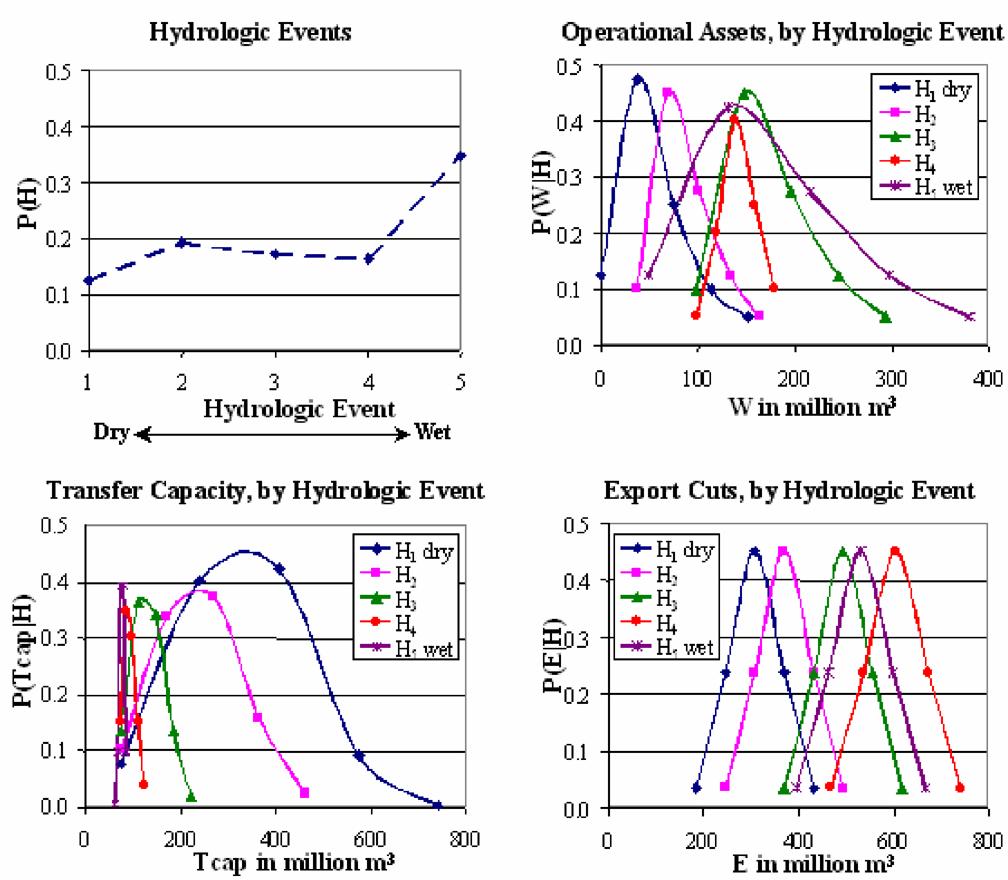

**Figure 3: Total Costs, by Hydrologic Event**

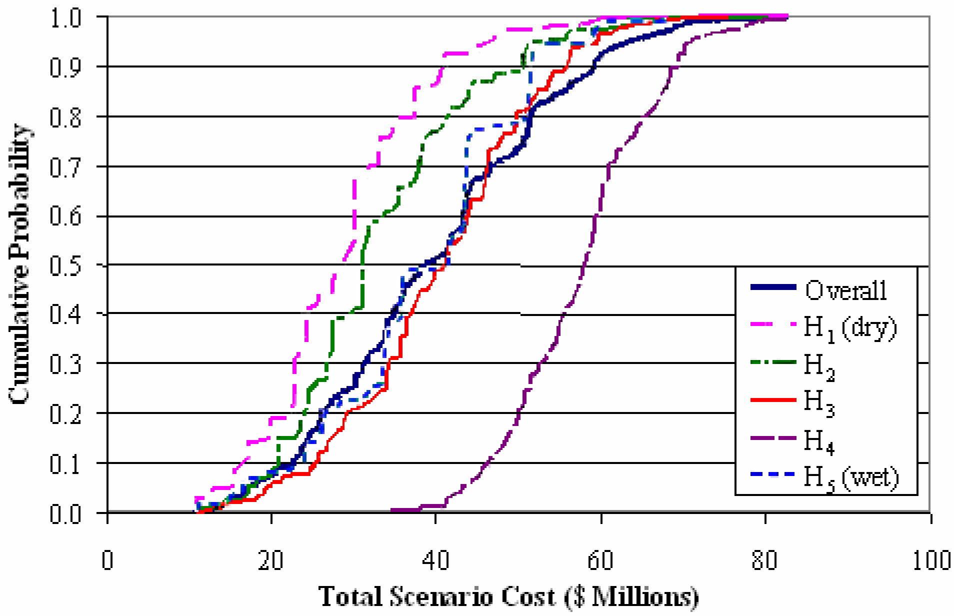


**Figure 4: Average Water Acquisitions, by Hydrologic Event and Purchase Type**

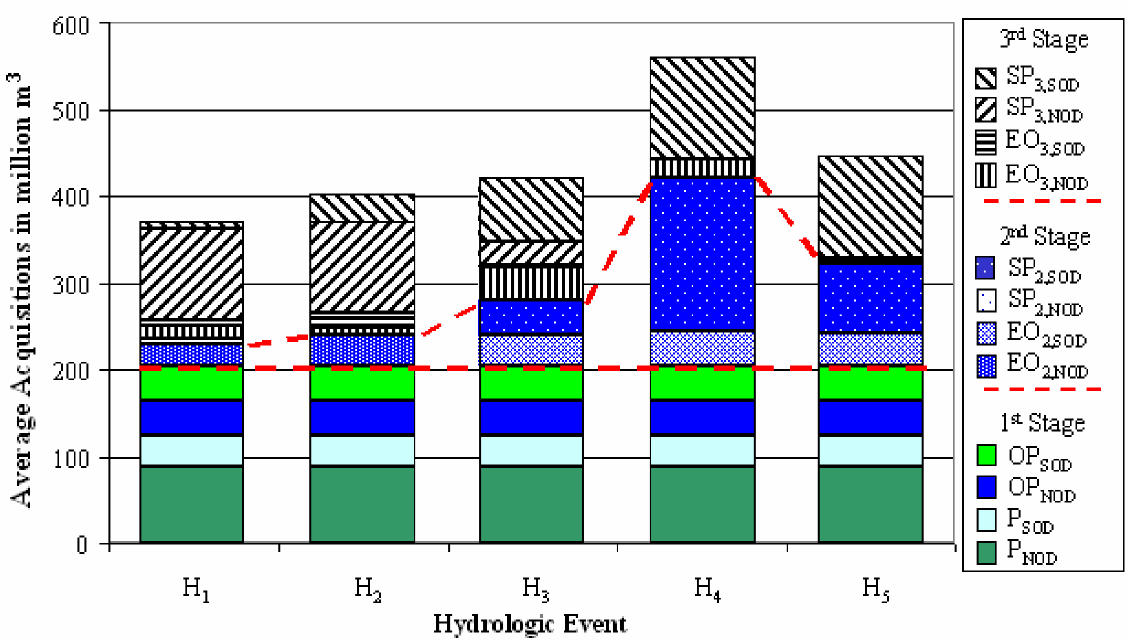

**Figure 5: Probability-Corrected Shadow Values for Export Cut Requirements by Hydrologic Event**