Optimization of Environmental Water Account Purchases with Uncertainty

By

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ABSTRACT

Increasing quantities of water have been dedicated to environmental uses in recent years, even in over-allocated water systems that experience frequent scarcity. State and federal agencies in California have established an Environmental Water Account (EWA) to buy water to protect endangered fish in the San Francisco Bay/ Sacramento-San Joaquin Delta. This paper presents a three-stage linear optimization model that identifies least-cost strategies for purchasing water for the EWA in the face of hydrologic, operational, and biological uncertainty. This approach minimizes the expected cost of water purchased to meet the uncertain needs of fish, using long-term, spot, and options purchases of water. It recommends optimal purchase strategies for current conditions, specifying the location, timing, or type of water purchases. The model can investigate how least-cost strategies change with 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. Details of the optimization model's application to California's EWA are provided along with a discussion of its utility for strategic planning and policy purposes. Limitations in the model's representation of EWA operations are discussed, as are recommendations for future model developments.

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CHAPTER 1: INTRODUCTION

Engineers spent much of the twentieth century modifying surface water systems across California and the entire United States to support human needs including irrigation, industrial processes, municipal consumption, and flood control. This momentum toward development and control of water resources began to shift with the changes in societal priorities that began with the environmental movement and legislation of the 1960s and ‘70s. More recently, the Endangered Species Act has forced changes as its requirements for the protection and recovery of listed species conflict with human demands for natural resources. Competition for water between human uses and endangered fish has drawn national attention to locations as disparate as Oregon, New Mexico, Florida, and California (Baron et al. 2002; Flug 1997). Management of water resources in each of these locations now focuses on how to operate engineered systems to meet the needs of people and fish. In California the state and federal governments have entered the statewide water market on behalf of endangered fish, buying water as needed to protect species in the San Francisco Bay/ Sacramento-San Joaquin Delta. Given the concurrent pressures on water resources to meet water demands for both endangered fish and people, significant attention is now focused on how to operate existing water supply systems and infrastructure to meet both demands as efficiently as possible (Howitt and Lund 1999; Wik 1995).

Czech and Krausman (1997) estimate that water infrastructure is the third most frequent cause of endangerment for all threatened and endangered species in the continental United States and Alaska, and its role in the fate of endangered fish is substantially greater. Efforts to restore instream flows to improve habitat have grown in recent years, and human use of water resources will continue and grow in the future (California Department of Water Resources 1998). Water that was once used for irrigation, manufacturing, hydropower, and human consumption has been re-allocated to endangered salmon in the Columbia River Basin in Washington and Oregon and to wildlife refuges in California's Central Valley. Similar arrangements are under consideration in New Mexico, Idaho, and Florida (Green and O'Connor 2001; van Eeten and Roe 2002). While the Endangered Species Act has been called "the pitbull of environmental laws", many efforts to meet its requirements have incorporated flexible, market-driven solutions (Thornton 1991).

Market-based approaches to potentially expensive environmental standards have gained increasing attention and support in the past decade, including notable application to the U.S. Acid Rain Program (Joskow and Schmalensee 1997). When resources, in the form of water or the right to create airborne pollutants, have economic value, markets often offer efficient means to meet requirements at lower economic cost. Markets have been used primarily to solve problems of pollution, often in the form of effluent charges or cap-and-trade systems (Stavins 2001). In these applications, regulators provide financial incentive not to pollute, either by charging a unit price for all effluent emitted or by requiring facilities to buy pollution credits on a market for any emissions above a pre-determined cap. In the cap-and-trade system, market forces encourage facilities that can reduce emissions at low costs to do so in excess of the level necessary to meet emission standards and to then sell the extra pollution credits on a market to those facilities for which reducing emissions is expensive. Thus the facilities with the lowest cost of reduction will reduce emissions by the greatest quantity, selling credits for their excess reductions to facilities for which such reductions would be more expensive. Similar markets have provided relief during droughts. During periods when water users in an intertied system receive significantly less water than they expect and need, water banks and markets have provided efficient means to move water from those who value it less to those for whom shortage is extremely expensive, including facilitating transfers from low-valued agriculture to urban uses (Howitt 1994).

Markets also have been used when environmental regulations require more of a natural resource such as a minimum instream flow or terrestrial habitat. Western water law, based on the doctrine of prior appropriation and usufructuary rights, initially prohibited the use of water for such non-consumptive purposes as instream flow. However, between 1986 and 1998, the eleven western-most states in the continental U.S. all modified their water codes to allow instream, environmental, and recreational beneficial uses. Between 1990 and 1997 these states saw over two million acre-feet of water leased and purchased for environmental application by state and federal agencies and environmental groups at a cost of $61 million (Landry 1998). The threat of low stream flow to endangered fish motivated many of these transactions, as the U.S. Fish and Wildlife Service has required the purchase of specific quantities of water each year in some of its biological opinions that establish legal requirements for the protection of endangered species. In addition, major public acquisition programs such as the Central Valley Project Improvement Act have vastly increased the presence of public agencies and environmental interests in water markets for the benefit of 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. This approach contrasts with litigation in that it acknowledges the current property owner's right to the property (be it land or water) and chooses to pay for the property rather than challenging its fundamental legal viability. Given the high costs and uncertain outcomes of litigation, such use of markets has gained appeal and use (Colby and D'Estree 2000).

California faced this decision between litigation and use of markets to ease conflict in the 1990s as endangered fish in the San Francisco Bay/ Sacramento-San Joaquin 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 harm. While the state believed that it had the authority to reduce pumping to meet the requirements of the Endangered Species Act, it had little interest in battling the water contractors in court. Although three years of these actions did result in litigation, the state focused its efforts on forming CALFED, a state and federal, multi-agency water management program which includes an Environmental Water Account (EWA). The EWA provides water to compensate for all fish-related reductions in water exported from the Delta, obtaining the compensatory water primarily through purchases on the statewide water market.

This paper presents a three-stage linear optimization model that identifies the least-cost strategies for purchasing water for the EWA to compensate for fish-related export cuts in the face of hydrologic, operational, and biological uncertainties. Previous work has used optimization models to examine the economic benefits of water markets in general (Brajer et al. 1989; Howe 1997; Howe et al. 1986) and in California (Draper et al. 2003; Jenkins et al. 2004). Two-stage linear programming has been used to maximize economic benefits of regional water management plans and minimize economic costs of protecting endangered fish in south Texas (Gillig et al. 2001; Gillig et al. 2004). Lund and Israel (1995a) also used two-stage linear optimization to examine the economic benefit of transfers and conservation measures for urban water supply. In addition, the Natural Heritage Institute (NHI) sponsored the development of a model to optimize water purchases for the EWA. The NHI model uses a Monte Carlo simulator to generate random combinations of hydrologic events and of operational assets, drawing data from results of a 1999 gaming exercise (Electric Power Research Institute 2002). The NHI model then uses a linear optimization engine to determine the optimal decisions for each individual trial or scenario, drawing on user-specified inputs for the cost and availability of water purchases. The NHI model presents optimal decisions for all trial in histograms of optimal results and provides additional statistical analysis as part of its output.

This paper begins with a more detailed introduction to the Environmental Water Account and exploration of its role in California's water market. It then presents the mathematical formulation of the optimization model, followed by its application to the

EWA and the associated results. Finally the paper addresses details of the results including the sensitivity analysis and conclusions and recommendations for further study.

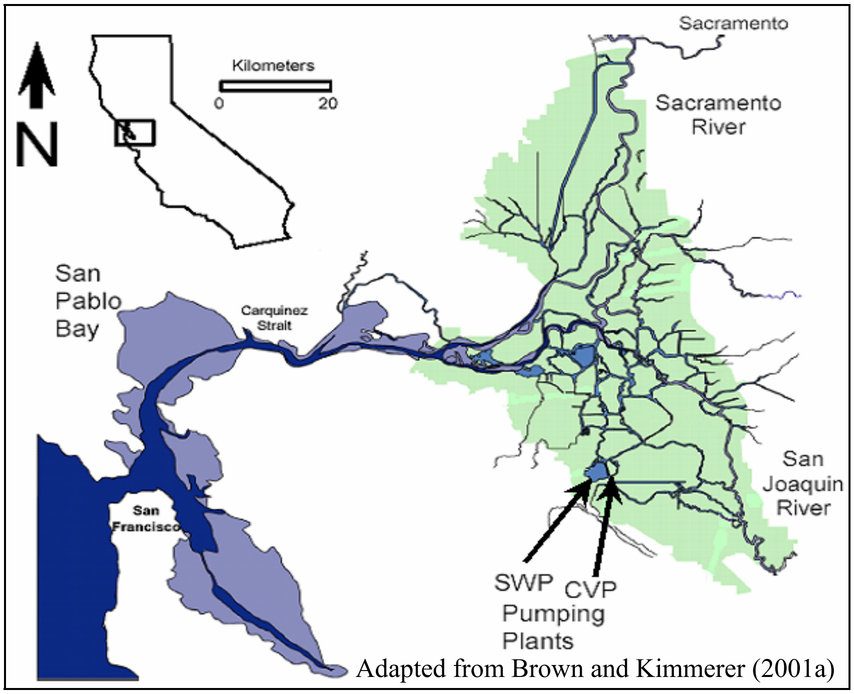
CHAPTER 2: ENVIRONMENTAL WATER ACCOUNT

The San Francisco Bay/ Sacramento-San Joaquin Delta (the Delta) is the largest estuary on the West Coast of the United States. It supports over 500 species of plants and animals while simultaneously providing water supplies for two thirds of California's residential and commercial users and over seven million acres of farm land (California Department of Water Resources 1995; Hill 2001). To manage such a complex and important resource, 21 state and federal agencies formed CALFED, an umbrella agency 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 exports of water from the Delta do not harm threatened or endangered species of fish. The State Water Project (SWP) and Central Valley Project (CVP), the state's two largest water projects, draw up to 15,000 and 8,000 acre-feet per day from their respective pumping facilities at the southern end of the Delta (see Figure 1). In the past water supplies were lost to consumptive use when regulators reduced pumping to protect fish. Water that went unpumped also went uncompensated, causing conflicts between consumers, regulators, and environmental advocates.

2.1 Structure of the EWA

The Environmental Water Account exists as 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 Project Agencies, which operate the SWP and CVP). The Management Agencies decide when to curtail pumping to protect endangered fish (primarily winter and spring run Chinook salmon, Delta smelt, and steelhead rainbow trout) and the EWA then reimburses the Project Agencies for all foregone water exports by transferring EWA water assets to the affected Project. The timing and volume of these pumping reductions, or export cuts, varies with hydrology and fish behavior, making them difficult to predict.

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



Adapted from Brown and Kimmerer (2001a)

The EWA is comprised of a variety of assets, some of which it can predict in advance and some of which depend on flows into the Delta and other external conditions. It may buy water through long-term, spot market, or options purchases. It also may adjust several of the water projects' operating procedures under specific conditions, allowing the EWA to benefit from increases in pumping during high flows, with the additional pumped water accruing to the EWA. In addition, when the EWA owes the Project Agencies water in a reservoir that then fills due to Project operations, the EWA's obligation to repay the Project Agencies is cancelled (CALFED Bay-Delta Authority 2000). The extra water collected through both of these means is known as the EWA's operational assets.

The EWA also has guaranteed access to 500 cubic feet per second of capacity at the SWP pumping plant for the months of July through August. This is a right solely to conveyance, but it guarantees the EWA capacity to transfer at least 60 thousand acre-feet (TAF) of water across the Delta at the end of each summer, giving it access to the water market north of the Delta, where water is generally more abundant and less expensive than it is south of the Delta. Additional capacity may be available for the EWA, especially in dry years when water contractors (who take priority over additional EWA transfers) make fewer transfers, but the EWA is unlikely to have access to much more than its guaranteed minimum pumping capacity in wet 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 in the Delta. Carriage water losses vary with hydrology and project operations, but generally range from 0 to 25 percent. EWA demands (in the form of export cuts) must be met at the projects' pumping facilities, which are considered south of the Delta as they form the bottleneck that defines the north/south split. Thus any water procured north of the Delta must be transferred from North to South, incurring carriage water losses and requiring the use of the EWA's cross-Delta transfer capacity.

2.2 EWA Operations

The EWA reimburses the Projects effectively at their pumping facilities where their supplies were reduced. Practically, this means that the EWA must provide water to the agencies either at the pumps or at another location south of the Delta where they can then use it to replenish their supplies or deliveries to their water contractors. The EWA often borrows water from the Projects at San Luis Reservoir, one of the Projects' main south of Delta storage facilities, during the spring and early summer months when it makes the majority of its export cuts. The EWA transfers most of its water across the Delta during the late summer, using those transfers to repay the Projects for earlier borrowing. When possible, the EWA schedules the upstream release of water that it is transferring across the Delta to improve instream habitat as an additional benefit of the transfer process.

The EWA seeks to protect multiple species of threatened and endangered fish in real time, modifying Project operations in response to actual ecological events rather than pre-determined, static standards. This results in time periods in which managers are operating the account for the primary benefit of different species, focusing more on salmon during the winter months and Delta Smelt in the spring. In addition, the EWA supplies water to augment other fishery protection measures that take place in April and May, further increasing the use of its assets in those months. In contrast, the EWA collects operational assets year-round as conditions in the Delta or reservoirs permit, with the majority collected from fall through spring. The EWA's cross-Delta transfers are heavily concentrated in the late summer when it has guaranteed access to pumping capacity, but it also has historically moved water across the Delta between June and December, as conditions permit. See Table 1 for details of operations to date.

Table 1: Average EWA Actions for 2001 – 2004 in Thousand Acre Feet

Month Action	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Export Cuts	-	-	8	56	17	26	22	129	4	-	-	-
% of total	-	-	3%	21%	7%	10%	8%	49%	1%	-	-	-
Cross-Delta Transfers	4	6	0.1	-	-	-	-	-	3	16	12	10
% of total	8%	11%	0%	-	-	-	-	-	6%	31%	24%	20%
Operational Assets	1	1	3	2	19	15	0.3	-	8	18	12	8
% of total	1%	1%	3%	2%	22%	17%	0%	-	9%	20%	14%	9%

The EWA currently operates within an annual budget, with operations depending on the state and federal governments' allocations in each year. The EWA addresses this financial uncertainty by including provisions in all water purchase contracts that make them contingent on funding (California Department of Water Resources and Kern County Water Agency 2004; California Department of Water Resources and Yuba County Water Agency 2004). To date, the EWA has not been constrained by its budget, shifting roughly $18 million in unused funding over from 2004 to 2005. EWA managers begin each year with a set of purchase goals that address the needs anticipated for each of five possible water year types commonly used by California Department of Water Resources and the U.S. Bureau of Reclamation to classify the water quantities available in the system. Based on these goals, managers attempt to secure purchases of approximately 75 TAF of water from known, inexpensive sources north of the Delta (usually the Yuba County Water Agency) early in the water year. This quantity represents the minimum amount that they expect to transfer across the Delta plus carriage water losses. Other early north of Delta purchases generally take the form of dry year options, which can be exercised subject to the availability of cross-Delta transfer capacity. Initial purchase targets for these transfers range from 0 to 185 TAF of additional north of Delta purchases, with the largest purchases in drier years (when additional transfer pumping capacity is likely to be available). These initial purchases have been made on an annual basis to date, but managers are exploring multi-year contracts for both purchases and options that can guarantee longer-term prices and access to water (CALFED Bay-Delta Authority 2004a). Finally, the EWA also seeks to enter into contracts with south of Delta sellers that are based on the annual availability of water to all water contractors from the Projects. These arrangements often take the form of wet year options, with target quantities ranging from no water in dry years to 170 TAF in the wettest years.

While the EWA has a defined and published set of goals for the quantity and location of its water purchases, actual budgetary, political, hydrologic, and market conditions are such that these purchases take place incrementally over several months, with negotiations starting in the fall but often not concluding until the spring. Other EWA activities follow a similar sequence. The state releases its initial forecast of water deliveries to its contractors at the beginning of December each year, with regular updates through the beginning of May. These dates result from California's weather patterns in which the vast majority of precipitation falls from late fall to spring and demand is highest from late spring through fall. Based on this and other forecasts of hydrologic conditions, EWA staff refine their own estimates of available transfer capacity across the Delta. They also consider the hydrologic forecasts in conjunction with their actions already in a given operational season to estimate how much more water they anticipate collecting in the form of operational assets and how much export cuts are likely to consume for the year. By the beginning of May, managers have a solid understanding of hydrologic conditions and have collected most of their operational assets, and their estimates of transfer capacity and export cuts are improving. By mid-summer, all of these quantities are known, and activities focus on transferring water and taking any remaining opportunities to collect operational assets.

2.3 EWA Performance

The EWA was initially created as an experiment with which to protect fish while maintaining deliveries to water users during a four-year period from 2000 through 2004. It included a commitment to annual peer reviews of its performance by an external panel of experts, and so it has received substantial scrutiny from both stakeholders and independent sources. Overall, it has received high marks for meeting multiple objectives with no precedent to provide guidance. Based on this success, the Management and Project Agencies have agreed to extend the EWA in its existing form through the end of 2007 while the agencies and other stakeholders negotiate the form of an anticipated long-term EWA (CALFED Bay-Delta Authority 2004b; Thompson et al. 2004).

While the EWA's overall performance has earned its renewal for three more years, it has had some failures. In its first year of operation, the EWA spent $65 million to buy 336 TAF of water and yet failed to protect winter-run Chinook salmon to the extent required by the U.S. Fish and Wildlife Service's biological opinion. Fisheries biologists misjudged the size of the migrating population and made 230 TAF of export cuts between January and April 2001 before realizing that the population exceeded estimates and their cuts had affected only the earliest 10 percent of the migration. They then allowed pumping to continue for the rest of the run without making export cuts out of concern that they would have no assets left with which to protect species later in the year. In the end, biologists estimate that almost six percent of the total migrating population was killed at the pumps, compared to the legal limit of two percent established by the biological opinion (Brown and Kimmerer 2001b). This early learning experience highlighted the importance of understanding the scale and timing of fish migrations and spurred significant improvement in the fish forecasts used to inform export cuts. Using these improved tools and with the experience of previous mistakes, subsequent years of EWA operations have kept the numbers of all endangered fish taken at the pumps below the levels specified by their respective biological opinions. By the EWA's fourth year of operation in 2003-4, it spent $19.6 million on 155 TAF of assets and succeeded in keeping take of Chinook salmon to approximately one quarter of the regulated level (CALFED Bay-Delta Authority 2004d). While this success is a function of fish behavior as much as EWA actions, it indicates a considerable amount of learning over the four years of EWA operations.

One challenge in evaluating the EWA's performance is the complexity of the lifecycles of each species of fish and of the many programs that seek to protect and restore their populations. The EWA is only one of many components in efforts by CALFED and other public and private groups to improve habitat upstream and in the Delta and to reduce the risk posed to fish by Project operations. Stakeholders cannot quantify the return on investment in the EWA in terms of fish saved per dollar or per acre-foot because it is impossible to isolate the effects of the EWA from the rest of the complex environment in which the fish exist. This lack of tangible performance measures has been a challenge to negotiations over a long-term EWA as parties on all sides of the discussion want to know the effects of their potential investment.

One clear accomplishment of the EWA is its success in bringing fisheries biologists and water project operators together to manage components of the statewide system jointly. Whereas these managers often had been at direct odds during past conflicts, the EWA has made fisheries protection part of the operators' consciousness and responsibility. Likewise, fisheries biologists now wrestle with the full water supply implications of each action taken to protect fish. Beyond the substantial improvement in relations between the groups, the shift in how each group plans to meet its differing primary objectives is fundamental, and has been recognized as a substantial benefit of the EWA in addition to its primary goals (EWA Review Panel 2005).

CHAPTER 3: EWA IN CALIFORNIA'S WATER MARKET

The statewide water market in California, from which the EWA purchases most of its assets, encompasses numerous types of water transfers. Three common types of transactions include multi-year transfers, spot market transfers, and contingent transfers or options purchases. Howitt (1998), Lund and Israel (1995b), and Howe (1997) all discuss these transfers in detail and Hill (1999) addresses their role in California. Their specific use by the EWA in the context of hydrologic and other uncertainties is discussed below.

Multi-year 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. While they avoid many of the legal and capital hurdles associated with purchasing the water right permanently, multi-year transfers impart similar stability in supply. They also may enjoy favorable prices, as the seller benefits from the ability to plan crops or other affected resources with the knowledge that the sale will take place. Multi-year 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 addition, options contracts, which are described below, can be implemented on a multi-year basis.

The EWA is currently investigating the possibility of entering into multi-year contracts, particularly to purchase water from the Yuba County Water Agency, located north of the Delta. Yuba has the distinct advantage of owning significant surface storage facilities, allowing it to sell stored water, which gives buyers the flexibility of taking delivery of water at their convenience, rather than at a specific time of year as is required by some sellers. This is particularly important for EWA operations, as it often has limited and date-specific access to cross-Delta transfer capacity. The EWA also is exploring the possibility of a multi-year contract with the Metropolitan Water District of Southern California (Metropolitan) in which the EWA would provide water to Metropolitan in dry years, Metropolitan would pay the EWA $55 per acre-foot for these deliveries, and then Metropolitan would provide the EWA with an equivalent volume of water in the wettest years at no cost (Fullerton 2005). Under such a contract the EWA would buy water in dry years at a price subsidized by Metropolitan and then effectively store that water with Metropolitan until wet years, when it would be returned in full at no cost. Both parties would receive relatively inexpensive water when their needs are greatest.

Spot market transfers offer flexible, short-term opportunities for buyers to meet immediate needs when they have made no previous arrangements. Spot market prices vary substantially in response to hydrology (e.g., the availability of water), location, water quality, and storage arrangements. Prices also vary with market conditions over the course of the year. Prices tend to increase in dry years when less water available for transfer. Prices in California are substantially higher south of the Delta as supplies are limited and water from the north must be transferred through the Projects' pumping facilities. Prices also increase later in the year as agricultural sellers have already planted crops that will be reduced or lost if water is sold. This model incorporates the effects of hydrology, location, and time of year on prices, but does not yet address water quality or storage.

The EWA has used spot market purchases to augment earlier purchases as the full extent of their exports become clear later in the year. In wet years, spot market prices are often low even south of the Delta as water contractors have plenty of water and many are interested in selling excess. However, spot purchases can be expensive in dryer years, as the EWA found in its first year of operations. Initial planning for the EWA assumed that it would buy most of its water south of the Delta, and so managers made purchases accordingly in 2000-2001, buying 231 TAF in the south and 105 TAF in the north. This resulted in a total expenditure of $65 million for that water year, which is by far the highest annual expense paid by the EWA to date (CALFED Bay-Delta Authority 2001). All of the 2000-01 purchases were on the spot market. Their high cost helped motivate EWA managers to explore other purchasing arrangements as budgetary allocations for the EWA decreased in subsequent years.

Contingent transfers, or options, offer buyers the opportunity to guarantee the availability and price of water when they do not yet know their needs. Options generally include two components: a fixed unit price of the option itself that guarantees access to the water and the strike price, or 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 options contracts and retains the possibility of using the water if the options go unexercised (Howitt 1998).

The EWA has increased its use of options since its first year of operations, purchasing 35 TAF of options north of the Delta and 49 TAF in the south in 2003-04. Because the EWA made fewer export cuts in this time period than it had in previous years, it left the south of Delta options unexercised while still paying $2.0 million for these water contracts (CALFED Bay-Delta Authority 2004c). While options include the risk of paying such contractual costs even in years when they remain unexercised, they offer flexibility that the EWA needs because of the significant differences in export cuts between wet and dry years. As the EWA refines its purchasing strategy and plans for the longer term, managers expect that options will continue to play a significant role in their purchases, with new arrangements such as the joint venture with Metropolitan offering additional savings.

The EWA is a unique party in the California water market as it relies on purchases in every year to provide the bulk of its assets. Whereas most buyers are water districts seeking to augment their existing supplies, the EWA has no such guaranteed assets, and so it must either buy or collect operational assets in every year to cover the demand of export cuts. This heavy dependence on the market means that the EWA is one of the biggest buyers in the state every year. This offers it some opportunities as a reliable and thus attractive buyer for some sellers. It also raises concerns with other prospective water buyers, who worry that such a large presence in a relatively small market will give the EWA inappropriate leverage and access to the best opportunities.

The EWA is also unusual in that its needs generally increase in wetter years, whereas municipal and agricultural demands diminish and water sources that do not flow through the Delta grow with increased precipitation. Thus, the EWA must procure its largest quantities of water when more water is available on the market, often at substantially lower prices. However, while wetter hydrologies make water less expensive for the EWA, they also reduce its ability to transfer water across the Delta, limiting its access to less expensive and more abundant northern sources.

CHAPTER 4: MATHEMATICAL FORMULATION

The Environmental Water Account currently functions on an annual basis, using annual budget appropriations to fund activities. Managers plan to enter into multi-year contracts to purchase water at favorable prices, but every contract is contingent on EWA funding. The model represents these long-term (annual and multi-year) contracts as first-stage decisions, since they hold regardless of conditions (excluding budgets) specific to each year. Purchase of options contracts also occurs in the first stage, as these may include multi-year contracts and even single-year options contracts often predate the availability of hydrologic and operational data. As the year progresses and more information becomes available on the availability of water, the operation of the Projects, and the behavior of endangered fish, EWA managers can choose to exercise options or purchase more water at higher spot market prices. If the EWA finds itself with water assets that exceed the demand for export cuts, then it can store that water in Project reservoirs at some risk to losing it if the reservoir fills during the rainy season. The water year is divided into three stages: (1) October through January, when little is known about the availability of water or the behavior of fish during the upcoming year, (2) February through April, when the approximate quantity of water available to the Projects becomes clear and the EWA collects operational assets, and (3) May through September when all conditions, including hydrology, operational opportunities, transfer capacity for the EWA across the Delta, and export cuts are known. The dates associated with these conceptual seasons may vary in real operations, but the mathematical representation of the model stages remains representative of the sequential availability of information. The problem is presented as a three-stage linear program (Loucks et al. 1981).

The model's objective is to minimize the average cost of EWA water purchases that are applied to compensate for fish-related export cuts, including long-term and spot purchases, options contracts, and the cost of exercising options. These costs are represented by Z, the total expected value cost for the EWA in one year of operation, in equation (1) below.

The decision variables include:

P_y = quantity of water purchased with multi-year agreements or on the spot market in the earliest season of the year (first stage), by location y, which can be divided into multiple variables for operational purposes;

OP_y = quantity of option contracts purchased in the first stage, by location y;

$SP_{x,y,h,i,j,k}$ = quantity of water purchased on the spot market in each model stage x at each location y (earlier stages have fewer subscripts as less information is available at these times);

$EO_{x,y,h,i,j,k}$ = quantity of options exercised by stage x and location y (earlier stages have fewer subscripts as less information is available at these times);

$S_{y,h,i,j,k}$ = amount of carryover storage at the end of the third stage, by location y, which is a decision variable that appears only in the constraints, and so it is not maximized or minimized, but rather provides slack on the demand and transfer constraints [equations (2) and (4)]; and

$T_{h,i,j,k}$ = the quantity of water transferred across the Delta, which is also a decision variable that appears only in constraints, linking the north of Delta and south of Delta decisions.

Random variables include:

H_h = hydrologic event or water year type, with H_1 being dry and H_5 wet;
$W_{h,i}$ = quantity of operational assets collected through changes to Project operations;
$Tcap_{h,j}$ = cross-Delta transfer capacity available to the EWA in each year; and
$E_{h,k}$ = quantity of foregone pumping (export cuts) for which the EWA must compensate the Projects.

The availability of operational assets and transfer capacity and the quantity of export cuts all vary with hydrology, making $W_{h,i}$; $Tcap_{h,j}$; and $E_{h,k}$ all dependent on h. For each random variable, p_h, $p_{h,i}$, $p_{h,j}$, or $p_{h,k}$ represents the probability of the specified event (e.g., hydrologic event = H_h, cross-Delta transfer capacity = $Tcap_{h,i}$, etc.)

None of these conditions are known in the first stage. H and W are known in the second stage and all are known in the third stage. In addition, α_h = percent of water transferred from the north that reaches the pumping facilities (effectively 1 – carriage water loss). This coefficient can vary with H, but it is currently set to a constant value of 0.85. The cost coefficient for each purchase by stage, location, type of purchase (e.g., P, OP, SP, etc.), and hydrologic event is $c_{x,y,z,h}$. We assume that values for all coefficients (or their expected values) are known from the beginning of the water year.

The resulting linear problem is:

Min

$$\begin{aligned} Z = \sum_{y} \Bigg\{ & c_{1,y,P}P_y + c_{1,y,OP}OP_y + \sum_{h=1}^{m}\sum_{i=1}^{m} p_h * p_{i|h} * \Big[c_{2,y,EO,h}EO_{2,y,h,i} + c_{2,y,SP,h}SP_{2,y,h,i} \\ & + \sum_{j=1}^{m}\sum_{k=1}^{m} p_{j|h} * p_{k|h} * \left(c_{3,y,EO,h}EO_{3,y,h,i,j,k} + c_{3,y,SP,h}SP_{3,y,h,i,j,k} \right) \Big] \Bigg\} \end{aligned}$$

(1)

Subject to

$$P_{SOD} + EO_{2,SOD,h,i} + SP_{2,SOD,h,i} + EO_{3,SOD,h,i,j,k} + SP_{3,SOD,h,i,j,k} - S_{SOD,h,i,j,k} + \tilde{W}_i + T_{h,i,j,k} \geq \tilde{E}_{k|h} \quad \forall\ h, i, j, k \tag{2}$$

$$EO_{2,y,h,i} + EO_{3,y,h,i,j,k} \leq OP_y \ \forall\ \ y, h, i, j, k \tag{3}$$

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

$$T_{h,i,j,k} \leq \tilde{T}cap_j \ \forall\ \ h, i, j, k \tag{5}$$

$$P_y;\ OP_y;\ EO_{x,y,h,i,j,k};\ SP_{x,y,h,i,j,k};\ T_{h,i,j,k} \geq 0 \ \ \forall\ \ x, y, h, i, j, k \tag{6}$$

Table 2: Definition of Subscripts in Model Formulation

Subscript	**Definition**	**Possible Values**

x	model stage number	x = 1, 2, 3
y	location	y = NOD, SOD
z	purchase type	z = P, OP, SP, EO, S
h	index of hydrologic events	h = 1, ..., m
i	index of operational assets available for each hydrologic event, h	i = 1, ... , m
j	index of transfer capacity available for each hydrologic event, h	j = 1, ..., m
k	index of export cuts for each hydrologic event, h	k = 1, ..., m
m	number of increments in each range of random variables	m = 5

The first constraint (2) represents the mass balance equation for each scenario ensuring that the demand represented by export cuts is met. The second constraint (3) prevents exercising more options than have been purchased in the first stage both north and south of the Delta. The third and fourth constraints [(4) and (5)] limit transfers such that it is impossible to transfer more water than is available north of the Delta or more than the available capacity, $Tcap_{h,j}$. The final constraint (6) ensures that the only decision variable that can take a negative value is S, or storage. Negative storage represents debt that the EWA owes to the Project Agencies, by location; for now, all storage is set to zero in this model run ($S_{y,h,i,j,k} = 0$).

The probability distributions for each random variable are discretized into $m = 5$ distinct values, resulting in m^4, or 625 distinct scenarios. These distributions can be refined and represented with more possible values and some distributions can be refined further than others; however, increasing the level of discretization increases the number of decision variables, constraints, and parameters exponentially, quickly straining the computational abilities of a desktop computer. This formulation includes

- $4 + 4*m^2 + 7*m^4$ decision variables,
- $4 + 4*m^2 + 14*m^4$ constraints,
- $4 + 12*m + 3*m^2$ parameters to estimate, and
- m^4 scenarios.

The number of parameters to estimate in the model include $4 + 10*m$ cost coefficients, m carriage water loss coefficients, and $m + 3*m^2$ probabilities and joint probabilities of events. Detailed representation of each random variable may be unnecessary and even disadvantageous in an optimizing screening tool such as the one described above as more information does not necessarily provide better or clearer suggestions of optimal strategy and requires increasing attention to estimating many additional parameter values. This optimization model is solved in GAMS and post processed using Excel (Brooke et al. 1998).

CHAPTER 5: APPLICATION

This model suggests least-cost strategies for location, timing, and types of water purchases by the EWA that meet the demand of export cuts at the lowest average cost, producing two primary categories of results: costs and water acquisition quantities. Each possible combination of uncertain events (m^4 of them) has an optimal set of purchase decisions. There is an optimal strategy of decisions that averages consequences over all uncertain scenarios. While the cost of the decisions might be higher than required for a specific single scenario, the strategies developed here minimize the average of all costs over all scenarios.

5.1 Model Inputs

The model results presented here are based on the inputs below, which reflect current hydrologic and operating conditions and EWA operations. These are specified by the user and can be adjusted to examine any alternative, including different hydrologic conditions such as global warming or policy changes that might affect the operating rules for the Projects and the EWA. Figure 2 shows the probability of different hydrologic "year types", taken from California Department of Water Resources publications (California Department of Water Resources 2004). Figure 3 indicates the probability distribution of operational assets for the EWA, estimated somewhat subjectively from recent EWA experiences and discussions with EWA technical staff; these vary with hydrologic year type (Spencer 2005).

Figure 2: Probability of Hydrologic Events

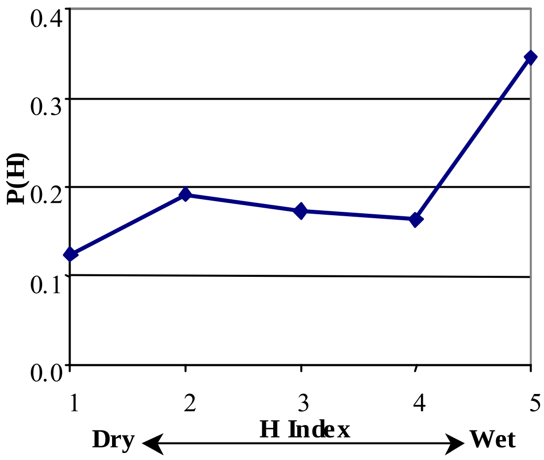


Figure 3: Probability of Operational Assets, by Hydrologic Event

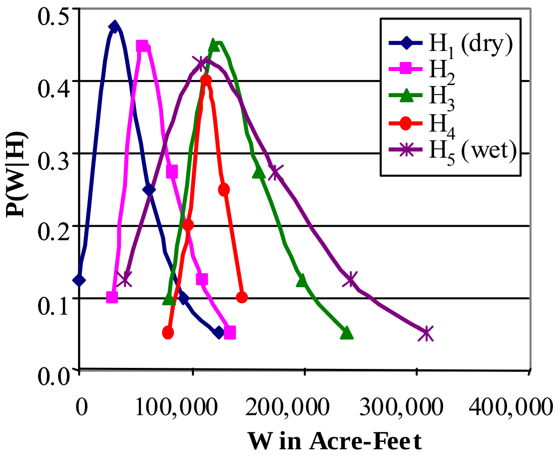


Figure 4 indicates the probability, varying with hydrologic year type, of EWA water transfer capacity from north of the Delta to south of the Delta, based on recent EWA experiences and discussions with EWA technical staff. Note that more transfer capacity tends to be available to EWA in dry years because there is less water in the system available for transfer by others with higher-priority access to cross-Delta pumping capacity. Figure 5 contains probability distributions for required export cuts, varying by hydrologic year type, again estimated somewhat subjectively based on recent experiences and discussions with agency staff. Table 3 contains cost coefficients for second and third-stage purchases of water and options north and south of the Delta, which vary with the seasons examined in the model and hydrologic year type. Costs for first stage water purchases are $75/AF north of the Delta and $160/AF in the south; north of Delta options contracts cost $10/AF and south of delta options contracts cost $20/AF. All cost estimates are based on recent purchase experiences within and outside of the EWA and on discussions with EWA staff.

Figure 4: Probability of Transfer Capacity, by Hydrologic Event

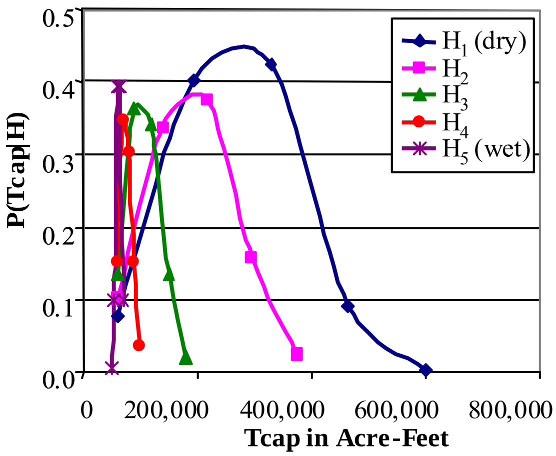


Figure 5: Probability of Export Cuts, by Hydrologic Event

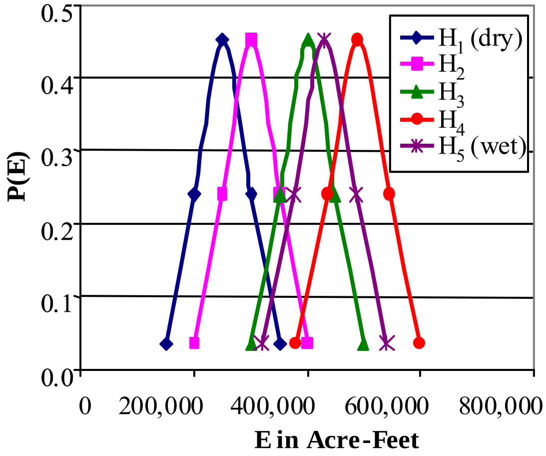


Table 3: Cost Coefficients for Decision Variables by Model Stage, Hydrologic Event, Purchase Type, and Location

Stage	Hydrologic Event	EO_{NOD} ($/AF)	EO_{SOD} ($/AF)	SP_{NOD} ($/AF)	SP_{SOD} ($/AF)
2	H_1	85	210	115	230
	H_2	80	200	100	220
	H_3	70	160	90	190
	H_4	60	140	75	165
	H_5	55	110	70	135
3	H_1	95	220	125	250
	H_2	90	210	110	240
	H_3	80	170	100	200
	H_4	70	150	85	170
	H_5	65	120	80	140

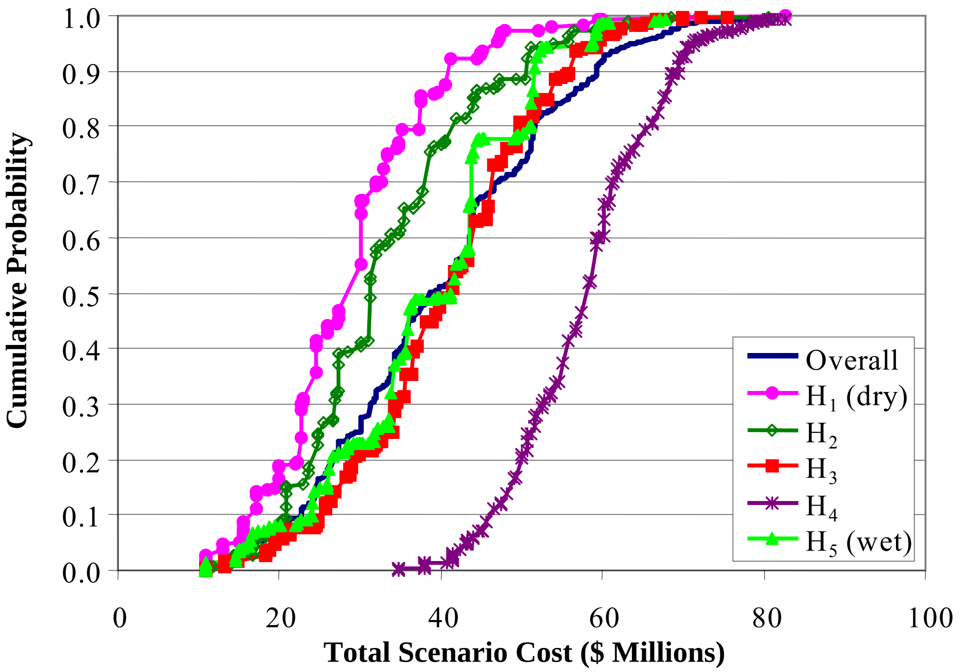
5.2 Cost Results

The average total cost over the range of scenarios described above is $38.6 million per year. This does not represent the cost of any single modeled year, but rather the average over every combination of events considered in the model, with its associated probability. Individual scenario costs range from $11.0 to $82.7 million per year. These costs translate to an average annual total purchase of 293 TAF, ranging from 100 to 538 TAF. These results are summarized below in a series of cumulative probability curves, showing the probability that costs (in dollars or acre feet) will be less than or equal to each point on the curve. Figure 6 shows the probability distribution of optimized EWA purchase costs, overall and for each of five hydrologic year types.

As additional information becomes available during the year, the probability of specific costs or optimal decisions changes for the remainder of that year. For example, the expected value cost for all scenarios is $38.6 million, whereas the expected value cost for the moderately dry hydrologic event (H_2) is $32.4 million and that given the moderately dry event and moderately low operational assets (H_2 and W_2) is $36.2

million. As additional information becomes available, the expected value cost approaches a single scenario cost as fewer uncertainties remain. Costs begin at $11.0 million, which is the cost of first stage decisions, which contribute to every scenario cost. In a few scenarios (low export cuts and high operational assets), these first-stage decisions and "free" operational assets are sufficient. Dry conditions with low operational assets and transfer capacity, but high demands (H_1; $W_{1,1}$; $Tcap_{1,1}$; $E_{1,5}$) provide the highest single scenario cost of $82.7 million. While this range of costs is wide enough to challenge the budget of a publicly funded program, its 25th and 75th percentile costs are $30 million and $50.8 million, respectively, providing a more targeted range for financial planning. The EWA's annual cost of water purchases to date has ranged from $19.6 million to $64.4 million, although their trajectory has been downward over its four years of operations (CALFED Bay-Delta Authority 2004b; CALFED Bay-Delta Authority 2004c).

Figure 6: Total Costs, by Hydrologic Event



The components of total EWA costs vary significantly across the modeled scenarios, but some patterns and generalizations emerge from the results. South of Delta spot purchases in the second and especially third stages frequently contribute the most to overall costs, although they contribute nothing in almost 30 percent of all cases. Figure 7 shows the probability distribution of each purchase type's contribution to overall costs, and Figure 8 shows the average cost of each type of purchase in each hydrologic event. While these averages lump many possible combinations of purchases, they demonstrate broad patterns in purchase strategy and cost by hydrologic event, which are useful for planning purposes.

Figure 7: Total Costs, by Purchase Type

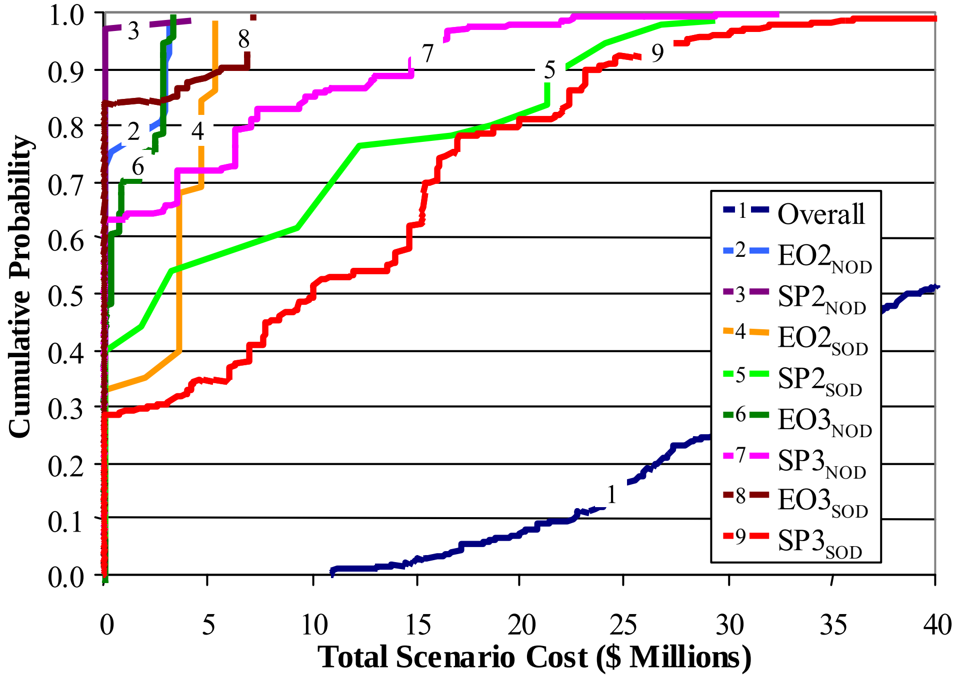
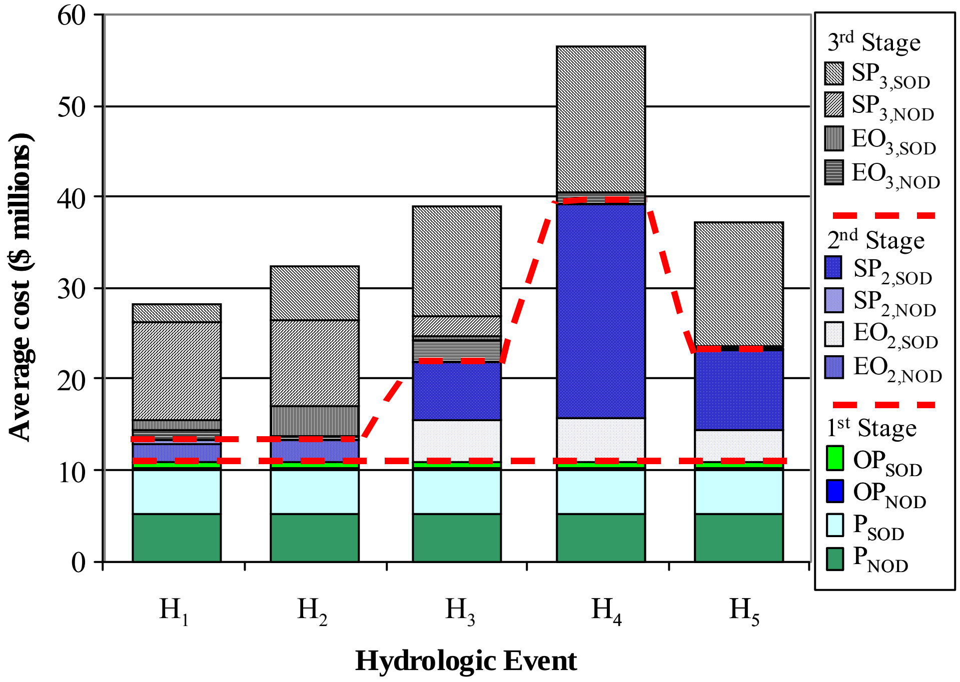


Figure 8: Average Costs, by Hydrologic Event and Purchase Type

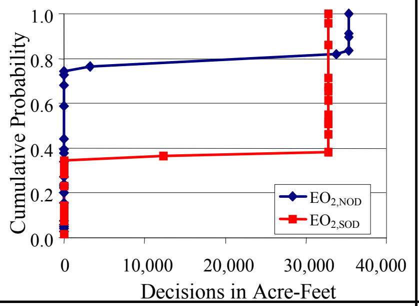


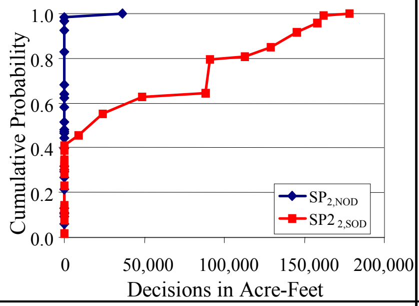
5.3 Least-Cost Decisions

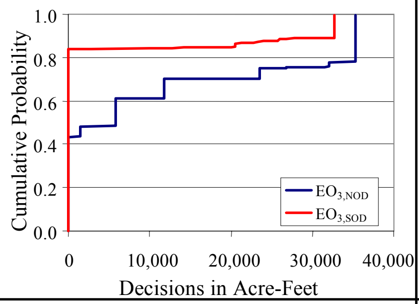
EWA purchase decisions occur in sequence, with increasing amounts of information as the year progresses. In reality, EWA managers make multi-year purchases based on demands they anticipate needing to meet in most years. For example, from our discussions, they expect export cuts to exceed 60 TAF in all years. They also expect to have at least 60 TAF of transfer capacity across the Delta, and so they are pursuing a multi-year contract for this quantity of water from an inexpensive source north of the Delta. As each operational season progresses, EWA managers refine estimates of their needs, consider acquisitions for that year to date, and plan additional acquisitions accordingly. Similarly, this model provides optimal first stage decisions that apply to all conditions, as well as decisions customized to each subsequent stage given decisions already made in the previous stage(s). This results in the minimum expected value cost over all combinations of random variables.

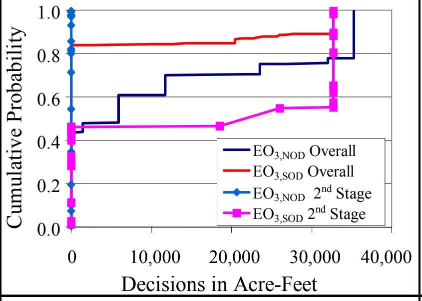
Figure 9 shows the evolution of these decisions with increasing information. It begins with first stage decisions that apply to all combinations of events along with exceedance curves that provide the probability that optimal quantities for each decision variable will be less than or equal to each point on the curve. Figure 9 then updates the same information for a given combination of second stage events (in this case, moderately dry conditions, H_2, with moderately low operational assets, $W_{2,2}$). The first stage decisions still hold (and are now past decisions), and the second stage probability curves are now specific quantities of exercised options and spot purchases. Optimal third stage decisions are still uncertain and are represented by an updated probability curve that incorporates the given second stage conditions. In its final column, Figure 9 represents the final given conditions (H_2; $W_{2,2}$; $Tcap_{2,2}$; $E_{2,2}$) and the associated decisions, which are now specific quantities for each decision variable. The probability curve for total costs and each average (e.g., expected value) cost also are updated over the course of the three model stages, with the first curve representing all possible events, the second updated to reflect the given second stage conditions, and the third resolving itself into the cost of decision for the specified scenario. The conditions presented in Figure 9 are: H_2 = moderately dry, $W_{2,2}$ = 56 TAF, $Tcap_{2,2}$ = 138.8 TAF, and $E_{2,2}$ = 250 TAF.

Figure 9: Evolution of EWA Decisions for Stage 1 through 3

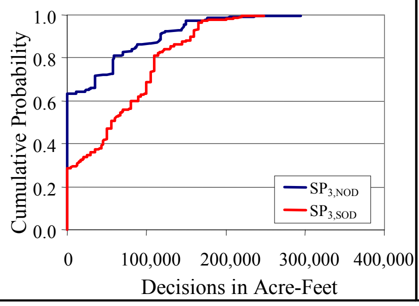
<table>
<tr><th colspan="2">Conditions
Decisions</th><th>Overall (All Scenarios)
<i>Stage 1 : October – January</i></th><th>H_2, W_2
<i>Stage 2 : February - April</i></th><th>H_2, W_2, $Tcap_2$, E_2
<i>Stage 3</i></th></tr>
<tr><td rowspan="2">1st Stage</td><td>Options</td><td>$OP_{NOD} = 35.3$ taf
$OP_{SOD} = 32.8$ af</td><td>-</td><td>-</td></tr>
<tr><td>Multi-Year Purchases</td><td>$P_{NOD} = 70.6$ taf
$P_{SOD} = 29.3$ taf</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">2nd Stage Decisions (February-April)</td><td>Exercise Options</td><td>


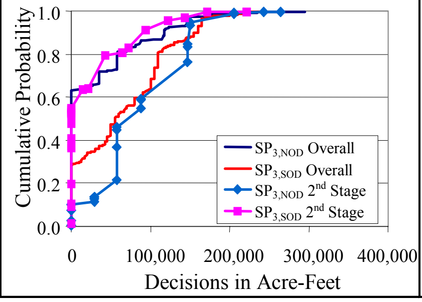
</td><td>$EO_{2,NOD,2,2} = 35.3$ taf
$EO_{2,SOD,2,2} = 0$ taf</td><td>-</td></tr>
<tr><td>Spot Purchases</td><td>


</td><td>$SP_{2,NOD,2,2} = 0$ taf
$SP_{2,SOD,2,2} = 0$ taf</td><td>-</td></tr>
<tr><td rowspan="2">3rd Stage Decisions (May-September)</td><td>Exercise Options</td><td>


</td><td>


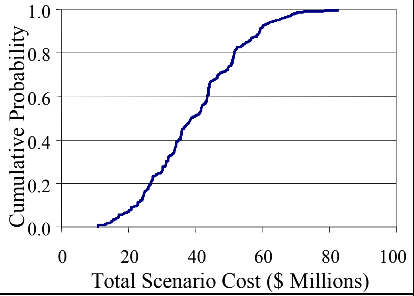
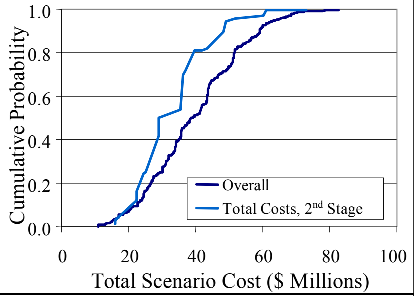
</td><td>$EO_{3,NOD,2,2,2,2}$
$= 0$ taf

$EO_{3,SOD,2.2.2,2}$
$= 26.0$ taf</td></tr>
<tr><td>Spot Purchases</td><td>


</td><td>


</td><td>$SP_{3,NOD,2,2,2,2}$
$= 57.4$ taf

$SP_{3,SOD,2,2,2,2}$
$= 0$ taf</td></tr>
</table>

Costs	Annual Cost			$26,845,800
	EV Cost	**$38,611,715**	**$36,244,617**	**$26,845,800**

5.3.1 October – January Decisions (Stage 1)

Optimal first stage decisions include the purchase of 70.6 TAF of water north of the Delta using multi-year or consistent one-year contracts as well as 35.3 TAF of options contracts. This initial purchase closely mirrors the EWA's current negotiations for a multi-year agreement to buy 75 TAF of water from the Yuba County Water Agency. Both EWA managers and the model are responding to the 60 TAF of guaranteed cross-Delta transfer capacity and the low cost of north of Delta water. Optimal first stage south of Delta decisions include 29.3 TAF of multi-year purchases plus an additional 32.8 TAF of options contracts. The lower quantities of south of Delta purchases reflect an unwillingness to commit to expensive south of Delta water in cases for which it might go unused. Such stranded south of Delta assets are rare, as optimal purchases (less carriage water losses) exceed export cuts in less than six percent of all years, with extra purchases exceeding 1 TAF in less than one percent of all years, as shown in Figure 10. In contrast, it is far more common to leave options unexercised, which incurs far less cost. In reality, EWA managers would store water that this model considers unused, un-transferred, and without value in Project reservoirs or groundwater banks for use in subsequent years. Additional flexibility from using or allowing storage in EWA operations should reduce average costs and make lower-cost multi-year purchases more attractive. However, leaving options unexercised is part of actual management, as the EWA demonstrated in the 2003-04 operating year. Transfer capacity, which does not have an explicit value in the model's objective function, but rather provides access to lower-cost, north of Delta purchases, also goes unused in approximately 23 percent of all scenarios, although the likelihood of excess or unused transfer capacity varies widely with hydrologic event, as shown in Figure 11.

Figure 10: Unused Water Assets

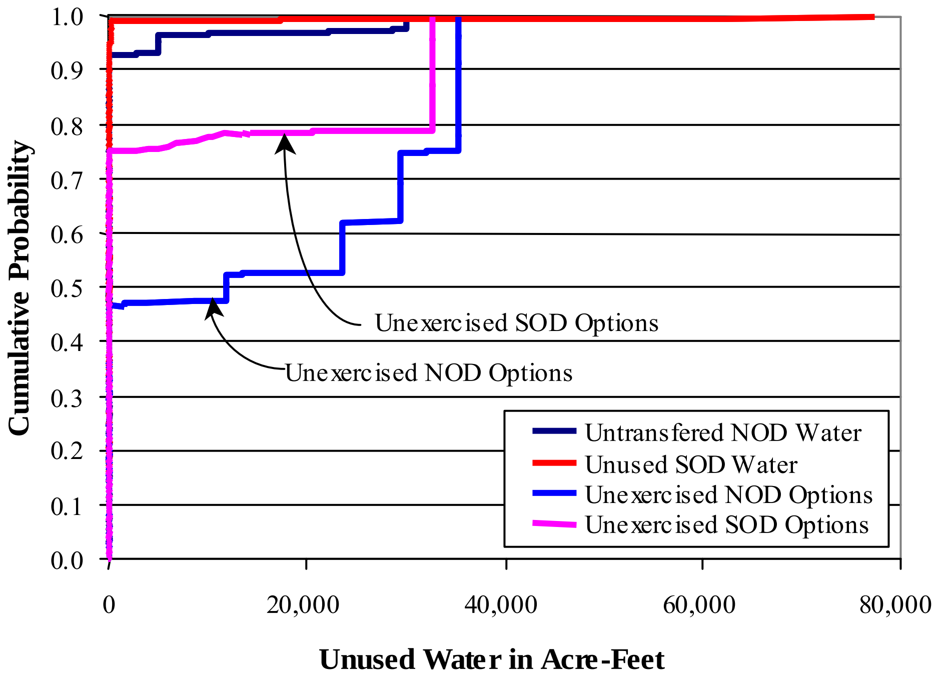
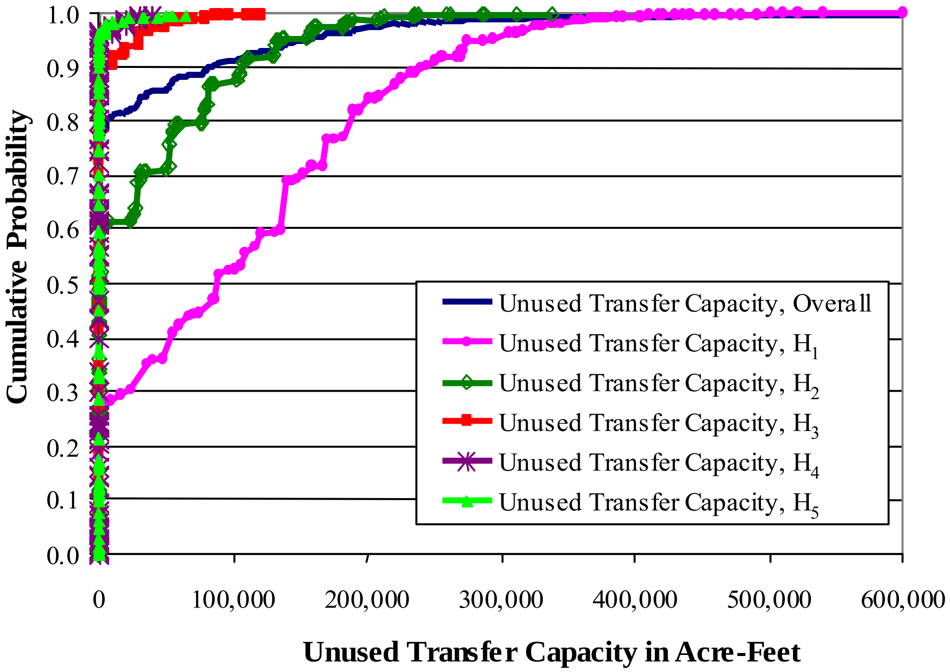

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative Probability
0
20,000
40,000
60,000
80,000
Unused Water in Acre-Feet
Unexercised SOD Options
Unexercised NOD Options
Untransfered NOD Water
Unused SOD Water
Unexercised NOD Options
Unexercised SOD Options

Figure 11: Unused Transfer Capacity, by Hydrologic Event



5.3.2 February – April Decisions (Stage 2)

The infrequency of second stage purchases north of the Delta indicates the remaining third-stage uncertainties regarding transfer capacity and export cuts. The model only exercises options or makes spot purchases north of the Delta at this stage in the drier hydrologic events and the lower quantities of operational assets (less than one year in four for exercising options and less than one year in 50 for spot purchases), as shown in Figure 9. This is a result of the strong relationship between dry conditions and higher transfer capacity across the Delta. While the available transfer capacity is unknown in the second stage, its strong tendency to increase with drier 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 the chances of successful transfer are high.

In contrast to the northern purchases, it is usually optimal to exercise second stage options in the south, mostly in wet years, and especially when operational assets are low. In moderately wet (H_4) years, which have the highest export cuts, it is optimal to exercise all south of Delta options in all cases. Sharp drops in water prices cause much of this wet year activity when water contractors south of the Delta receive higher deliveries from the state and federal projects. The quantity of options exercised is limited by the first stage decision to purchase only 32.8 TAF of options contracts. However, second stage 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 180 TAF. 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 high. Under no circumstances is it optimal to make spot purchases or exercise options both north and south of the Delta under the same conditions in the second stage.

5.3.3 May – September Decisions (Stage 3)

Third stage decisions vary widely, reflecting full information on transfer capacity and export cuts, as well as hydrology and operational assets. They represent the decisions required to meet the demand of export cuts when earlier decisions are insufficient, and so third stage decisions are greatest when export cuts are greatest.

Exercising options in the third stage reflects not only overall export cuts, but also both the first stage decision of how many options contracts to purchase and any second stage decision to exercise options. These influences result in defined ranges of decisions with vertical jumps (representing many identical decisions) in the cumulative probability distribution. It also results in seemingly counterintuitive decisions, which are driven by previous actions. For example, third stage options are exercised north of the Delta most often in average (H_3) hydrologic events, taking advantage of instances in which transfer capacity is available. North of Delta options are exercised least often in dry years in the third stage because it is very common to exercise all options in the second stage for these conditions. Similarly, the most common hydrologic event in which to exercise third stage options south of the Delta is H_2, which is moderately dry. In these instances, no options were exercised in the second stage, leaving options available for instances of high export cuts in the third stage. Over all hydrologic events, it is less common to exercise third stage options south of the Delta than north because so many options were already exercised in the south during the second stage (so few options remain). In the specific scenario presented in Figure 9, the model exercises all 35.3 TAF of available options north of the Delta in the second stage (reflecting moderately dry conditions and the high likelihood of large transfer capacity) but exercises no south of Delta second stage options. In the third stage, it has no north of Delta options left to exercise, but it exercises 26.0 TAF of south of Delta options to cover the difference between all previous and north of Delta acquisitions and the required export cuts.

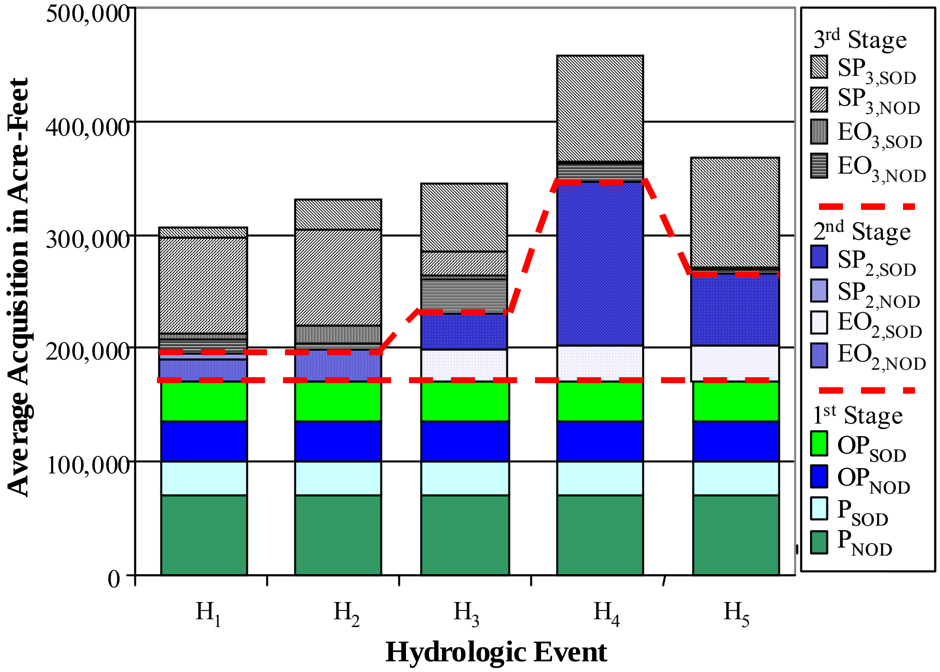
The vast majority of north of Delta third stage spot purchases are made in dry years, and the frequency and magnitude of purchases decrease with increasingly wet hydrologic events. In the driest two year types, some third stage spot purchases are made north of the Delta in 87 percent of scenarios, with the largest purchases approaching 300 TAF. In contrast, third stage spot purchases are never optimal north of the Delta for the wettest (H_5) events and are optimal in less than five percent of scenarios in the moderately wet (H_4) case, as transfer capacity limits the utility of third stage north of Delta spot purchases in most of these instances. South of Delta third stage spot purchases show the opposite patterns; they are optimal in 95 percent of wetter (H_4 and H_5) scenarios, with maximum purchases reaching 230 TAF. 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, although maximum purchases in those periods are the highest of all, approaching 250 TAF. The large differences across hydrologic events in the distribution of spot purchases by location are caused primarily by the wide spread of south of Delta water prices and cross-Delta transfer capacity across hydrologic events. Because third stage spot purchases south of the Delta are over $100 more expensive in dry years than in wet, the purchase strategies for those years are very different.

CHAPTER 6: DISCUSSION OF RESULTS

One challenge of multi-stage linear optimization models is interpreting output. Because model results encompass all combinations of reasonably foreseeable conditions (in the form of random variables), this model recommends actions for many different scenarios (625 scenarios in this case), which require organization to extract general patterns, promising operating policies, and lessons learned. Based on the model run presented above, it is possible to draw the following conclusions:

- Water year type is the single best predictor of EWA costs, as it affects the market price of water, availability of operational assets, cross-Delta transfer capacity, and quantity of export cuts, as shown in Figure 12.
- Availability of transfer capacity determines the location of purchases, as water is both more abundant and less expensive north of the Delta.
- Operational assets and export cuts affect the total cost of EWA 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.
- Allowing the use of storage and debt should buffer the effects of unusually low or high export cuts, respectively, reducing average costs and making lower-cost multi-year purchases more attractive for EWA operations.

Figure 12: Average Water Acquisitions, by Hydrologic Event and Purchase Type



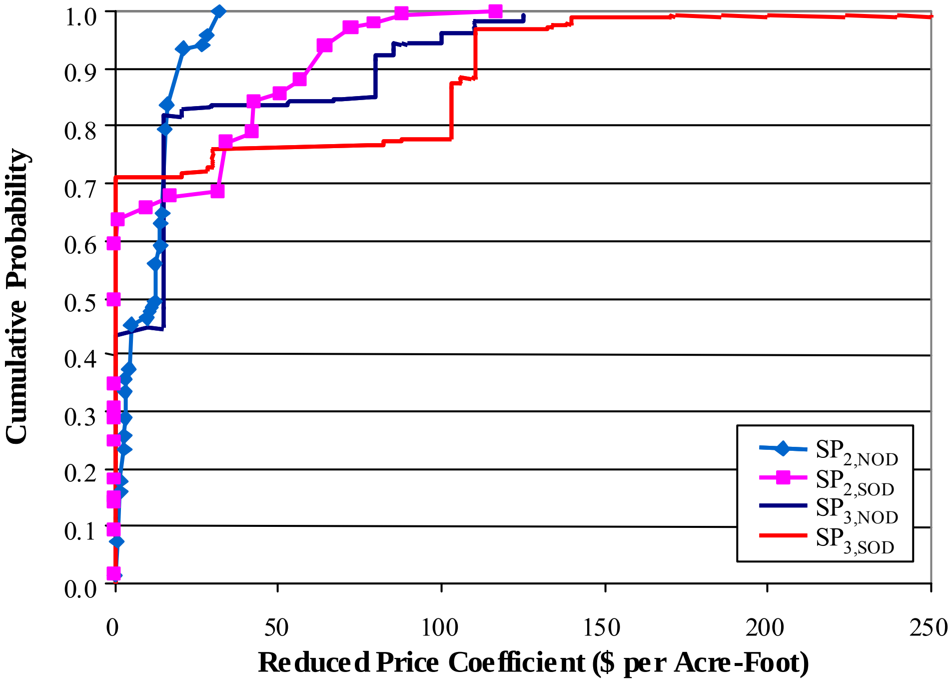
6.1 Sensitivity Analysis

The results presented above are specific to the model inputs used in this example. While a wide range of alternative parameter estimates can be examined easily with new model runs, the sensitivity analysis provided by standard linear optimization software can be useful in evaluating how sensitive results are to uncertainties in many inputs individually. This type of information is particularly important when using such a model to plan purchases, as non-economic factors may also contribute to purchase decisions, making it important to understand what drives least-cost decisions and total costs. This information is also useful for identifying bottlenecks or important constraints in the system, where changes would have the greatest benefit.

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 would have the greatest effect on average costs (Hillier and Lieberman 2001). Representing the change to the optimal value of the objective function (here, the lowest average cost) that would result from changing a parameter or loosening a constraint by one unit, high shadow values indicate where additional refinement to parameter estimates, or changes in conditions, would be most valuable. Range-of-basis information on cost coefficients indicates how much the price of decisions (weighted by their probabilities in many cases) could change before changing the structure of acquisition decisions. Range of basis information is particularly useful to EWA managers as they evaluate potential water purchases. This model provides reduced price coefficients, which are the amount by which water price coefficients would have to decrease for it to become optimal to purchase that water for a given combined event scenario. This is the reduced cost, corrected for the probability associated with each scenario. For decisions that are already optimal in a given set of conditions there is no reduced price coefficient, as the purchase is optimal as is.

The highest reduced price coefficients for third stage spot purchases equal price of the next-lowest cost alternative water source ($125 per acre-foot north of the Delta and $250 per acre-foot in the south in dry years). These occur when first and second stage decisions are sufficient to cover export cuts, making additional third stage purchases superfluous. In these cases, spot purchases would have to have no cost (i.e., their price coefficient would have to be reduced to zero) to enter the optimal solution. While reduced price coefficients reach their equivalent cost coefficient in cases when spot purchases are not needed to cover export cuts, they also frequently equal zero, as third stage spot purchases are optimal given their current cost coefficients, with no reductions needed. Reduced price coefficients are generally lower for second stage spot purchases, never reaching the full value of the cost coefficient itself, as shown in Figure 13. This is because there are no instances in which previous (here, first stage) decisions have completely covered export cuts for all possible remaining scenarios, and so any second stage decision has the potential to become optimal if its price is low enough.

Figure 13: Probability-Corrected Reduced Price Coefficients for Spot Purchases



Reduced price coefficients for the cost of exercising options exhibit similar patterns, with high reductions needed to make a decision optimal when other decisions have already covered export cuts. However, there are instances in which it is not possible to exercise third stage options because of decisions in the first and second stage. In these cases, the reduced price coefficient reflects the impossibility of making such a decision, making its value both large and meaningless. Figure 14 provides the range of viable coefficients with their associated probabilities. Because the decision to exercise options in the second stage is limited only by the quantity of options contracts purchased, there is no such difficulty in calculating reduced price coefficients for them. Maximum reduced price coefficients are $17.10 per acre-foot for exercising options north of the Delta and $98.35 per acre-foot for exercising them in the south. As was true for second stage spot purchases, these values never reach the full cost coefficient associated with the decisions, as it is always possible for the decision to enter the optimal solution if its cost is low enough. There are no reduced price coefficients for first stage decisions because they are already selected at their current prices.

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. By correcting for the probability associated with each possible combination of events, as we did for the reduced price coefficients, this indicates how much relaxing a coefficient by one unit would save in a specific scenario. Figure 15 and Table 4 list the range of scenario-specific shadow values associated with each constraint, and Figure 16 provides details of the shadow values associated with export cut requirements for each hydrologic event. These indicate the value (or cost) of changing resources or requirements associated with each of the constraints in the optimization model. The constraint on exercising options behaves the same as the reduced price coefficient for third stage options described above, and so its maximum value reflects interaction with multiple decisions rather than the actual change in cost associated with that scenario.

Figure 14: Probability-Corrected Reduced Price Coefficient for Exercising Options

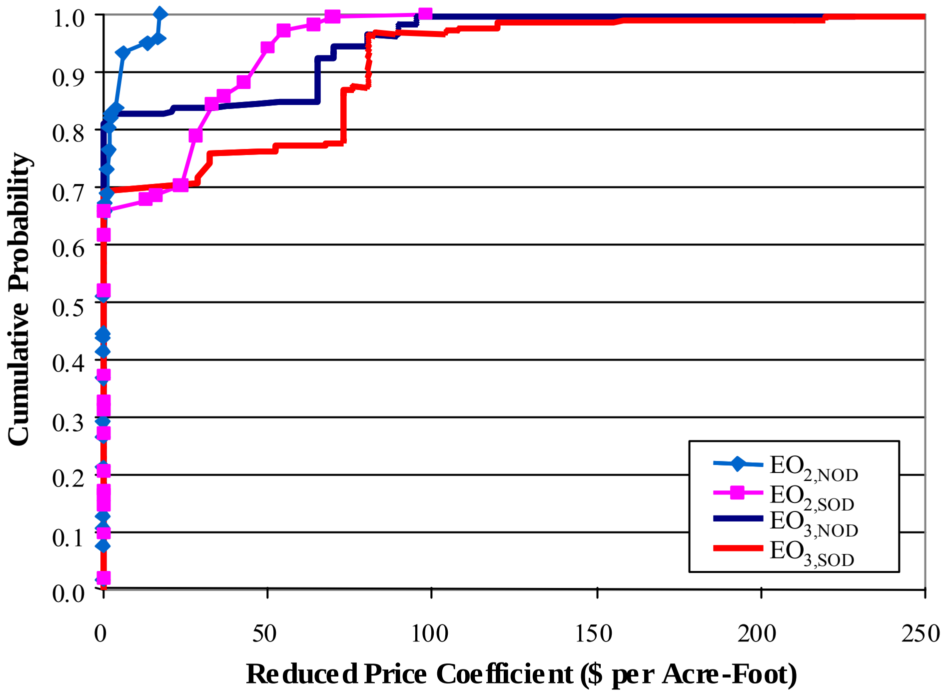


Figure 15: Probability-Corrected Shadow Values for Small Changes in EWA Resources and Commitments

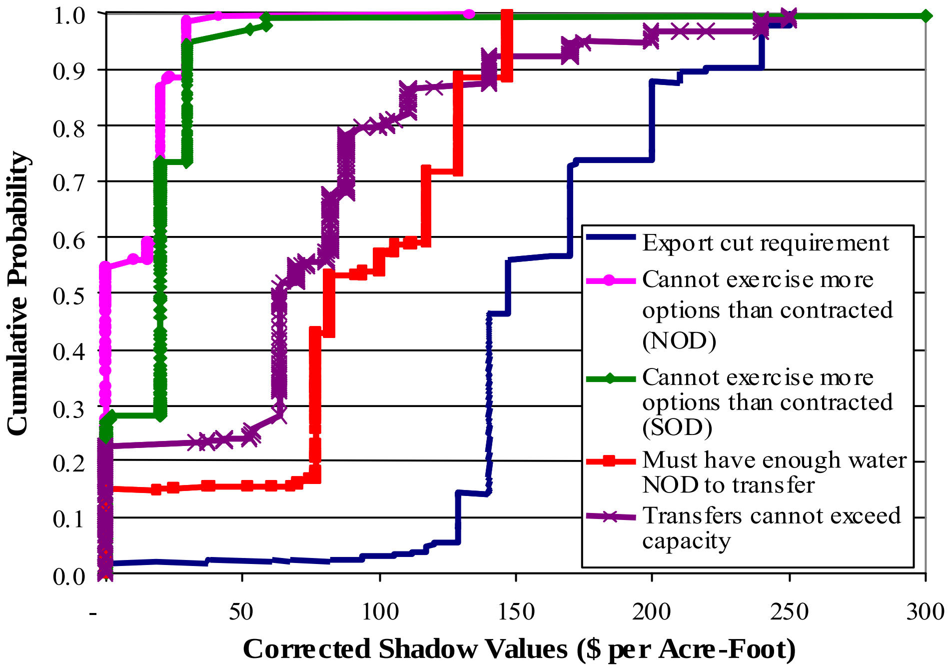


Figure 16: Probability-Corrected Shadow Values for Export Cut Requirements, by Hydrologic Event

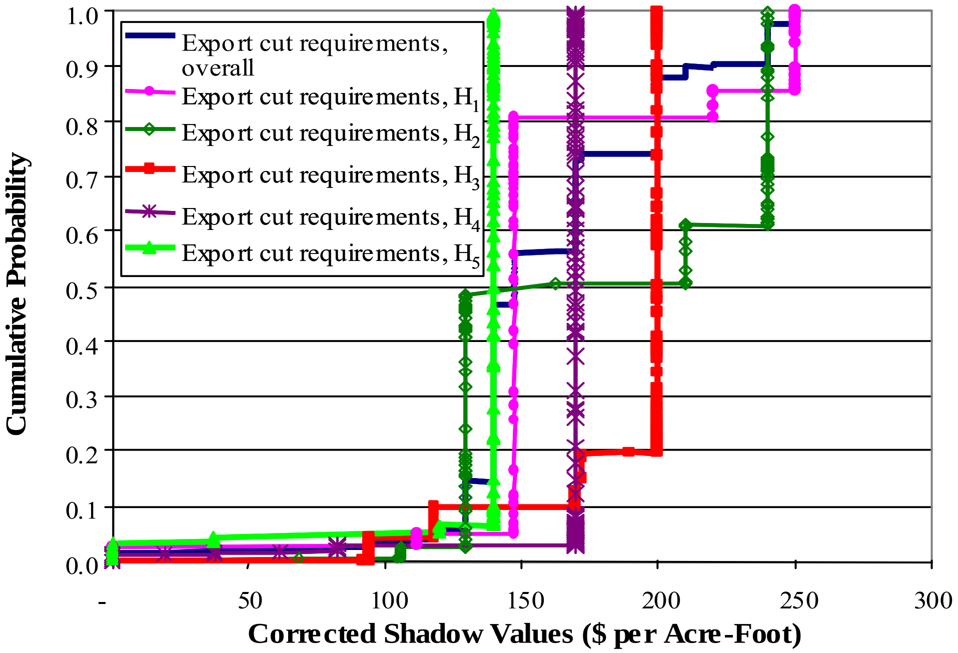


Table 4: Probability-Corrected Shadow Values for Small Changes in EWA Resources and Commitments

Resource or Commitment	Corrected Shadow Values ($/AF)
Export cut requirements (Equation 2)	
Maximum	$250
Median	$147
Option exercise limits north of Delta (Equation 3a)	
Maximum	$134
Median	$0
Option exercise limits south of Delta (Equation 3b)	
Maximum	n/a
Median	$20
NOD water availability for transfer south of Delta (Equation 4)	
Maximum	$147
Median	$ 82
Through-Delta transfer capacity (Equation 5)	
Maximum	$250
Median	$70

The simplest and perhaps most flexible form of sensitivity analysis provided by any model is the output from successive model runs with different inputs. This model runs quickly, and so such analyses are relatively easy, allowing modelers to examine the response of the entire set of modeled conditions to changes in inputs. For example, reducing export cut quantities by 50 TAF across all conditions reduces the average total cost by \$8.0 million to \$30.6 million per year. This type of information could be particularly useful to EWA managers as they consider how to make export cuts in an era of limited financial budgets. In addition, some stakeholders involved in negotiating the terms of a long-term EWA are interested in the difference between the minimum quantity of export cuts needed to protect endangered fish at the levels required by the biological opinions (some would call this the legal minimum of export cuts) and any additional export cuts that are made to improve the species' overall viability and chance of recovery. These distinctions may play an important role in apportioning the cost of a long-term EWA between parties or in the development of EWA export cut strategies for agencies with alternative environmental uses for some EWA funds, and so the ability to model the costs of different resource inputs or requirements has significant strategic and planning value.

6.2 Model Limitations

All models are simplifications of reality. Here, we assume that all parameter values are known. There is some variability in the price paid for options and purchases even within the same location, hydrologic event, and time frame. The EWA negotiates costs with every seller individually, and so while managers may know the price that they pay for water procured through a multi-year contract, other prices are subject to negotiation and may reflect a host of tangible and intangible factors unique to each transaction. This concern is especially relevant because the EWA buys a large fraction of the water transferred on the California water market each year, giving it exceptional leverage to negotiate prices. As the water market grows to include more and larger buyers and as the novelty of the EWA decreases, this effect may also diminish. Thus far, however, negotiations for water have involved the same learning process as other features of the EWA, as managers understand the conditions and uncertainties that they face and the sellers from whom they buy better each year. This learning process makes water prices particularly hard to predict at the beginning of the operating season. While using the expected value of cost and probability parameters is sufficient for a linear formulation that minimizes overall average costs, incorporating the probabilistic range of price and probability parameters will broaden the overall probability distributions of costs and decisions (Wagner 1975).

Carriage water losses depend less on human factors such as experience and more on a complex set of conditions that affect the state of the Delta at any point in time. Carriage water losses generally decrease when more water flows into the Delta, as exports from the pumping facilities influence the local hydrology less during high flows. However, even in wet years, carriage water losses can be significant during the dry summer months, as part of exports must be dedicated to water quality and other standards. Adding to the difficulty in predicting these parameters are non-hydrologic variables such as noxious weeds in the southern Delta, which can impede project pumping, particularly in the late summer (Spencer 2005).

Perhaps the model's single greatest limitation is its current exclusion of carryover storage and debt. The EWA can carry water stored in Project reservoirs over to the subsequent water year, at some risk that its water will be lost if the reservoir fills during flood control operations in the wet season. The EWA has developed agreements with south of Delta water contractors to exchange or bank water that is in imminent threat of spilling, but such arrangements generally involve some losses and costs. Nevertheless, the ability to keep excess water at the end of the year and apply some portion of it to the following year's export cuts buffers some of the EWA's costs, giving it value for water that is currently evaluated as lost. While this formulation does not provide a value for storage, it is clear that water stored in a reservoir has value, which would offset some cost of purchases in years when purchases exceed export cuts.

Perhaps more importantly, the EWA can go into debt to the Projects up to a limit of 100 TAF, which could provide an attractive alternative to making expensive third stage spot purchases when export cuts exceed expectations. As described in Table 4, one acre-foot of debt can reduce the total cost of operations in a single year by as much as $71. Scaled up to larger volumes, this could provide significant savings. Carrying such debt has the added advantage of the possibility of spilling at no cost. If the EWA owes a project water in a specific reservoir (most often San Luis, south of the Delta) and that reservoir fills due to normal project operations, then the EWA's debt is spilled, or erased at no cost. While this possibility makes debt appealing, the EWA is unlikely to choose to carry great debt, as it must be ready to repay any debt in the following year in addition to covering the cost of that year's export cuts. In addition, carrying large quantities of debt on a regular basis could pose political difficulties with water contractors.

Finally, this model minimizes the average cost of EWA purchases under the assumption that the EWA must compensate for the full quantity of export cuts. In reality, the EWA operates within a limited financial budget every year and makes its export cuts accordingly. While the EWA is expected to make sufficient cuts to protect endangered species of fish to at least the levels specified by the biological opinions, budgetary considerations are likely to influence the quantity of water purchases and export cuts 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.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Models such as this can assist in planning for the EWA, providing an efficient and risk-free way to explore a wide array of EWA actions and opportunities. As the EWA explores new approaches to the relatively novel challenge of providing water for environmental protection, tools that permit it to experiment at no 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 are struggling with similar conflicts between water reliability and fishery protection.

7.1 Conclusions

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 (Electric Power Research Institute 2002). Probabilistic optimization models such as the three-stage linear programming model presented here for the Environmental

Water Account further offer a means of exploring a much wider and more complex range of decision alternatives and combinations of options considering major uncertainties than would be possible with traditional simulation models alone. Applications can focus on new approaches to current strategy, including adjusting the location, timing, or type of purchases. They also can investigate how least-cost and effective 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 for the EWA. The 2004 EWA Review Panel recently suggested that models should incorporate uncertainty and address the range of possible outcomes, rather than a single answer based on a single sequence of events (EWA Review Panel 2005). The probabilistic approach described here does just that, examining a wide range of outcome events specified by the user.

With the current model application, south of Delta spot purchases (second and third stage) dominate both the quantity and cost of water purchases in wet years. In dry years, third stage spot purchases north of the Delta dominate. This heavy reliance on a combination of late-stage and earlier south of Delta spot purchases is safe but relatively expensive, using purchases that have little or no risk of going unused, but which are more expensive than less certain alternatives. As is often true in water management, greater flexibility reduces costs for EWA 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 provided here, as each provides EWA 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 model can also explore how such purchase strategies change with our understanding of hydrologic, economic, and environmental variability.

This model formulation also illustrates the value of modeling and economic-engineering optimization tools to policymakers. As market-based solutions like the EWA are applied to conflicts over water for the environment in other locations, analytic tools such as this model can help to impart lessons learned in California. While each physical and political setting is unique, linear optimization tools are easy to customize and can help other programs develop their own purchase strategies. Even the results of this model as it is applied to the EWA can provide examples of how environmental water purchasing strategies respond to hydrologic, operational, economic, and biological influences.

7.2 Recommendations for Future Study

This paper provides the basic formulation for a probabilistic optimization model that can be used directly or modified to address many questions regarding EWA operations. The following recommendations highlight areas that are likely to be particularly useful to EWA managers for modifying this model for a wider range of EWA policy, planning, and operational purposes.

1. Reformulate the linear program to minimize water deficits (i.e., the difference between purchases and export cuts) within a specified, perhaps probabilistic, financial budget.

2. Develop appropriate values, limits, and costs for storage and refine its representation to better reflect EWA use of storage and debt. This could include the addition of a random variable to reflect the probability of spilling debt (or stored assets), by hydrologic event.
3. Consider applying Marques' (2004) method for modeling long-term conjunctive use to EWA storage and debt, using a large body of storage to accumulate and withdraw water over a range of events, with the average of all inputs (storage) and withdrawals (debt) set equal to zero. Such an arrangement might be possible in cooperation with large south of Delta contractors that own significant local storage. Parties such as Metropolitan or the Kern Water Bank could enter into such a contract with the EWA for an insurance fee or other form of compensation.
4. Represent additional details of EWA operations, including its use of the source shift arrangement in San Luis Reservoir and the hydropower and pumping costs and credits associated with its operations.
5. Disaggregate the current lumped representation of sellers on the water market to differentiate sellers on the San Joaquin River who are both south and upstream of the Delta and differentiate between sellers within each location if cost data support such distinctions.
6. Conduct a more thorough sensitivity analysis, focusing particularly on the range of basis for cost coefficients, which can provide information that would help negotiate favorable contracts to purchase water.
7. Investigate the importance of uncertainties in predicting the scale and timing of fish migrations on EWA planning. This could include a multi-stage optimization tool that would allow the Management Agencies to consider the effects of their export cut decisions on the multiple species of concern. At its most basic, this could include moving the random variable for export cuts ($E_{h,k}$) to the first or second stage in the current formulation and re-running the model to derive a rough estimate of the value of accurate forecasts of fishery needs in the form of export cuts. A larger reformulation would be for Management Agencies to use the model to make water allocations to different purposes (e.g., species of fish) in different stages to maximize the production of various species within a given expected value cost, a form of multi-objective optimization.

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APPENDIX A: MODEL CODE

A.1 GAMS Code

```
Sets
   stage           stage in the water year                    /1, 2, 3/
   loc             location                                   /NOD, SOD/
   lim             max or min for carryover storage           /min, max/
   H               represents predicted hydrology             /H1*H5/
   purch_type      type of purchase                           /OP, EO, SP,S/
   W               variable assets available                  /W1*W5/
   b               H probability component                    /PofH/
   i               W probability components                   /Qw, PofQw/
   Tcap            available transfer capacity                /Tcap1*Tcap5/
   j               T probability components                   /Qt, PofQt/
   E               demand as export cuts                      /E1*E5/
   k               E probability components                   /Qe, PofQe/      ;

$include C:\Documents and Settings\Sarah\My Documents\Thesis\d=5\C. Spencer
run\input mod.txt
Variables
   P1(loc)                       quantity of purchase prior to operations season
   OP(loc)                       quantity of options contracts purchased in AF
   EO2(loc, H, W)                quantity of options exercised in stage 2 in AF
   EO3(loc, H, W, Tcap, E)       quantity of options exercised in stage 3 in AF
   SP2(loc, H, W)                quantity of spot purchases in stage 2 in AF
   SP3(loc, H, W, Tcap, E)       quantity of spot purchases in stage 3 in AF
   S(loc, H, W, Tcap, E)         quantity of end-of-year carryover storage in AF
   T(H, W, Tcap, E)              quantity of water transferred NOD to SOD
   Z                             total cost   ;
  Positive variables OP, SP1, EO2, EO3, SP2, SP3, T   ;
Equations
   tot_cost                         total cost and objective function given initial storage
   opt_const(loc,H,W,Tcap,E)        can't exercise more options than you purchased
   demand_const(H,W,Tcap,E)         must meet export requirements
   trans_const1(H,W,Tcap,E)         can't transfer more water than you have NOD
   trans_const2(H,W,Tcap,E)         transfer can't exceed available capacity
   stor_const1(loc,H,W,Tcap,E)      upper bound storage constraints
   stor_const2(loc,H,W,Tcap,E)      lower bound storage constraints  ;
```

```
opt_const(loc,H,W,Tcap,E)..   EO2(loc,H,W) + EO3(loc,H,W,Tcap,E) =l= OP(loc)  ;
demand_const(H,W,Tcap,E)..    SP1("SOD") + ProbW(H,W,"Qw") + EO2("SOD",H,W)
          + SP2("SOD",H,W) + EO3("SOD",H,W,Tcap,E) + SP3("SOD",H,W,Tcap,E) +
          T(H,W,Tcap,E) =g= ProbE(H,E,"Qe")   ;
trans_const1(H,W,Tcap,E)..    alpha* ( SP1("NOD") + EO2("NOD",H,W) +
          SP2("NOD",H,W) + EO3("NOD",H,W,Tcap,E) + SP3("NOD",H,W,Tcap,E) –
          S("NOD",H,W,Tcap,E) ) =g= T(H,W,Tcap,E)   ;
trans_const2(H,W,Tcap,E)..    T(H,W,Tcap,E) =l= ProbTcap(H,Tcap,"Qt")    ;
stor_const1(loc,H,W,Tcap,E).. S(loc,H,W,Tcap,E) =l= S_limit("max",loc)   ;
stor_const2(loc,H,W,Tcap,E).. S(loc,H,W,Tcap,E) =g= S_limit("min",loc)   ;
tot_cost..  Z =e=   sum( loc, cost("1","H1","OP",loc)*OP(loc) +
          cost("1","H1","SP",loc)*SP1(loc) )
          + sum( (H,W,loc), ProbH(H,"PofH") * ProbW(H,W,"PofQw") *
          (cost("2",H,"EO",loc)*EO2(loc,H,W) + cost("2",H,"SP",loc)*SP2(loc,H,W)
          + sum( (Tcap,E),   ProbTcap(H,Tcap,"PofQt") * ProbE(H,E,"PofQe") *
          (cost("3",H,"EO",loc)*EO3(loc,H,W,Tcap,E) +
          cost("3",H,"SP",loc)*SP3(loc,H,W,Tcap,E) )      )         )          )    ;

Model    three_stage
          /tot_cost,opt_const,demand_const,trans_const1,trans_const2,stor_const1,
          stor_const2/   ;
three_stage.OptFile = 1;
Solve    three_stage using LP minimizing Z   ;
```

A.2 Input File

```
Scalar   alpha   % of water reaching pumps from NOD storage = (1 - carriage water loss)
       /      .85      /;
Table    S_limit(lim,loc)        storage capacity for EWA assets in AF
              NOD     SOD
       min     0        0
       max    0        0

Table    cost(stage, H, purch_type, loc)    unit price of water ($ per AF)
                        OP.NOD  OP.SOD  EO.NOD  EO.SOD  SP.NOD  SP.SOD  S.NOD  S.SOD
     1   .    H1        10.0    20      0       0       75      160     0      0
     1   .    H2        10.0    20      0       0       75      160     0      0
     1   .    H3        10.0    20      0       0       75      160     0      0
     1   .    H4        10.0    20      0       0       75      160     0      0
     1   .    H5        10.0    20      0       0       75      160     0      0
     2   .    H1        0       0       85      210     115     230     0      0
     2   .    H2        0       0       80      200     100     220     0      0
     2   .    H3        0       0       70      160     90      190     0      0
     2   .    H4        0       0       60      140     75      165     0      0
     2   .    H5        0       0       55      110     70      135     0      0
     3   .    H1        0       0       95      220     125     250     70     160
     3   .    H2        0       0       90      210     110     240     68     158
```

```
        3  .  H3     0         0         80        170       100       200     66         156
        3  .  H4     0         0         70        150       85        170     64         154
        3  .  H5     0         0         65        120       80        140     62         152
Table   ProbH(H,b) probability associated with each hydrology
                  PofH
          H1      0.125000000000000
          H2      0.192307692307692
          H3      0.173076923076923
          H4      0.163461538461538
          H5      0.346153846153846
Table   ProbW(H,W,i) annual quantity of variable assets available in AF
                                Qw            PofQw
          H1            W1      0             0.125000000000000
          H1     .      W2      30750         0.475000000000000
          H1     .      W3      61500         0.250000000000000
          H1     .      W4      92250         0.100000000000000
          H1     .      W5      123000        0.050000000000000
          H2     .      W1      30000         0.100000000000000
          H2     .      W2      56000         0.450000000000000
          H2     .      W3      82000         0.275000000000000
          H2     .      W4      108000        0.125000000000000
          H2     .      W5      134000        0.050000000000000
          H3     .      W1      80000         0.100000000000000
          H3     .      W2      119500        0.450000000000000
          H3     .      W3      159000        0.275000000000000
          H3     .      W4      198500        0.125000000000000
          H3     .      W5      238000        0.050000000000000
          H4     .      W1      80000         0.050000000000000
          H4     .      W2      96250         0.200000000000000
          H4     .      W3      112500        0.400000000000000
          H4     .      W4      128750        0.250000000000000
          H4     .      W5      145000        0.100000000000000
          H5     .      W1      40000         0.125000000000000
          H5     .      W2      107000        0.425000000000000
          H5     .      W3      174000        0.275000000000000
          H5     .      W4      241000        0.125000000000000
          H5     .      W5      308000        0.050000000000000
Table   ProbTcap(H,Tcap,j) annual quantity of available transfer capacity in AF
                                 Qt           PofQt
          H1     .     Tcap1     60000        0.077776892668050
          H1     .     Tcap2     195000       0.402284234000507
          H1     .     Tcap3     330000       0.423138323835706
          H1     .     Tcap4     465000       0.092775918922934
          H1     .     Tcap5     600000       0.003992944538194
          H2     .     Tcap1     60000        0.102845298304985
          H2     .     Tcap2     138750       0.337536990193249
```

H2	.	Tcap3	217500	0.375557619769853
H2	.	Tcap4	296250	0.158472101936266
H2	.	Tcap5	375000	0.024238022572412
H3	.	Tcap1	60000	0.135905197722809
H3	.	Tcap2	90000	0.364094802058912
H3	.	Tcap3	120000	0.341344740459283
H3	.	Tcap4	150000	0.135905197722809
H3	.	Tcap5	180000	0.021400094812952
H4	.	Tcap1	60000	0.152444822306160
H4	.	Tcap2	70000	0.347555177475561
H4	.	Tcap3	80000	0.304317079843229
H4	.	Tcap4	90000	0.152444822306160
H4	.	Tcap5	100000	0.038174074194263
H5	.	Tcap1	50000	0.006121235268309
H5	.	Tcap2	55000	0.099528603817372
H5	.	Tcap3	60000	0.394350160696040
H5	.	Tcap4	65000	0.394350161132599
H5	.	Tcap5	70000	0.099440159226935

Table ProbE(H,E,k) annual EWA export cuts in AF

			Qe	PofQe
H1	.	E1	150000	0.035930265513823
H1	.	E2	200000	0.238322799424729
H1	.	E3	250000	0.451493870122895
H1	.	E4	300000	0.238322799424729
H1	.	E5	350000	0.034580298290588
H2	.	E1	200000	0.035930265513823
H2	.	E2	250000	0.238322799424729
H2	.	E3	300000	0.451493870122895
H2	.	E4	350000	0.238322799424729
H2	.	E5	400000	0.034580298290588
H3	.	E1	300000	0.035930265513823
H3	.	E2	350000	0.238322799424729
H3	.	E3	400000	0.451493870122895
H3	.	E4	450000	0.238322799424729
H3	.	E5	500000	0.034580298290588
H4	.	E1	380000	0.035930265513823
H4	.	E2	435000	0.238322799424729
H4	.	E3	490000	0.451493870122895
H4	.	E4	545000	0.238322799424729
H4	.	E5	600000	0.034580298290588
H5	.	E1	320000	0.035930265513823
H5	.	E2	375000	0.238322799424729
H5	.	E3	430000	0.451493870122895
H5	.	E4	485000	0.238322799424729
H5	.	E5	540000	0.034580298290588