Developing Portfolios of Water Supply Transfers

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ABSTRACT

Most cities rely on firm water supply capacity to meet demand, but increasing scarcity and supply costs are encouraging greater use of temporary transfers (e.g., spot leases, options). This raises questions regarding how best to coordinate the use of these transfers in meeting cost and reliability objectives. This work combines a hydrologic-water market simulation with an optimization approach to identify portfolios of permanent rights, options and leases that minimize expected costs of meeting a city's annual demand with a specified reliability. Spot market prices are linked to hydrologic conditions and described by monthly lease price distributions which are used to price options via a risk neutral approach. Monthly choices regarding when and how much water to acquire through temporary transfers are made on the basis of anticipatory decision rules related to the ratio of expected supply-to-expected demand. The simulation is linked with an algorithm that uses an implicit filtering search method designed for solution surfaces that exhibit high frequency, low amplitude noise. This simulation-optimization approach is applied to a region that currently supports an active water market, with results suggesting that the use of temporary transfers can reduce expected water supply costs substantially, while still maintaining high reliability levels. Also evaluated are tradeoffs between expected costs and cost variability that occur with variation in a portfolio's distribution of rights, options and leases. While this work represents firm supply capacity as permanent water rights, a similar approach could be used to develop portfolios integrating options and/or leases with hard supply infrastructure.

Keywords: water supply, hydrologic-economic modeling, water markets, options

INTRODUCTION

Rising water demand and concerns over scarcity have driven an increasing number of regions to explore market-based approaches to water resource management (Anderson and Hill 1997; Easter et al. 1998; National Research Council 2001). Nonetheless, most water markets remain relatively unsophisticated, with transactions involving only permanent transfers of water rights. While a number of studies have shown that permanent transfers encourage long-term allocation efficiency (Brookshire et al. 2004; Chang and Griffin 1992; Colby et al. 1993; Griffin and Boadu 1992; Hearne and Easter 1997; Howe et al. 1986; Howe and Goemans 2003; Nieuwoudt and Armitage 2004; Saliba 1987; Young 1986), such transfers provide a less effective means of managing short-term scarcity. Rising demand in many regions has increased the level of economic and social disruption brought about by seasonal droughts, consequently some markets are beginning to support a more sophisticated menu of temporary transfers (Howitt 1998). In response, some researchers have investigated the potential efficiency gains associated with "spot market" leases (Characklis et al. 1999; Smith and Marin 1993; Vaux and Howitt 1984) and options (Hamilton et al. 1989; Howitt 1998; Jercich 1997; McCarl et al. 1999; Michelsen and Young 1993; Villinski 2004; Watters 1995).

Spot market leasing generally involves the immediate transfer of "wet" water, with the lease price subject to considerable variability based on supply and demand conditions. A typical option agreement involves an initial payment that guarantees the purchaser the right to lease water at a later date at an agreed upon "exercise" price. The certainty inherent in the exercise price can make options an attractive hedge against spot market price volatility, while providing the additional advantage of postponing transfer decisions (and full payment) until better information is available. Both leases and options improve market flexibility relative to permanent transfers alone, allowing water users to more rapidly adapt to changing conditions while meeting their reliability goals with a reduced volume of "firm" capacity. As leases and options have become more widely available, there has been increased interest in how water users might coordinate the use of these instruments to achieve the dual objectives of maintaining water supply reliability and lowering supply costs.

Several previous studies have used either linear or stochastic programming techniques to identify combinations of supply alternatives, including infrastructure, transfers and conservation, that minimize the expected costs of meeting urban water demand (Jenkins and Lund 2000; Lund and Israel 1995; Watkins and McKinney 1999; Wilchfort and Lund 1997). In general, these methods have involved some form of two stage model in which the first step involves a hydrologic simulation that is used to establish a discrete set of supply scenarios. This information is combined with price and usage data to develop least cost combinations of long-term (e.g., reservoirs) and short-term supply alternatives (e.g., leases, options), with results suggesting that the coordinated use of short-term transfers can reduce costs.

This work focuses solely on market-based transfers, but expands on earlier studies by employing a simulation-optimization approach that allows for the exploration of some issues that have received less attention in previous work. In particular, this work describes portfolio development from the perspective of a utility manager seeking to minimize water supply costs. In many earlier studies a city's decision to acquire water via leases or options and its actual receipt of the water occur within a single time period. While these periods have often been long enough (3 to 6 months) that this is not unreasonable, such an approach assumes that the city buys and acquires water at exactly the time it is needed or, alternatively, that the city has perfect information regarding its future needs at the time it makes a purchase. Even in a market where transactions can be completed quickly, such a scenario is at odds with the risk averse nature of utilities who will generally seek to augment supply in advance of a shortfall (i.e. without perfect information). Toward that end, this work identifies anticipatory decision rules, using the ratio of expected supply to expected demand as the basis for determining when (and how much) to lease/exercise. These rules could provide a utility with a decisionmaking framework for arriving at a least cost solution using information as it becomes available throughout the year.

Uncertainty with respect to spot market prices will also be a concern when developing portfolios that include temporary transfers. In this work spot lease prices are represented as distributions (based on actual market data) and this information is used to price options in a risk neutral manner consistent with financial theory (Black and Scholes 1973; Hull 1999). The use of lease price distributions provides the additional benefit of allowing for the calculation of both expected cost and cost variability. This is a potentially important distinction because while minimizing expected supply costs is certainly important, it is likely that cost variability will also play a role in decisions regarding a portfolio's suitability. Cost variability has been considered before, Watkins and McKinney (1997) describe a relatively elegant approach that incorporates consideration of both expected supply costs and their variance when identifying an optimal solution, however, their approach assumes a symmetrically distributed objective function (essentially cost). This may not be the case in many regions, a point made more significant given that the risk of high costs associated with asymmetric tails in the distribution may have a significant impact on decisionmaking.

The modeling approach employed consists of a hydrologic-market simulation embedded within a search-based optimization algorithm. This methodology is designed to identify the portfolio of rights, options and/or leases that minimizes expected costs while meeting constraints related to both supply reliability and (in some cases) cost variability. When minimizing the expected costs of water supply in a stochastic environment, computational burden can be a particular concern. In water supply problems, the expected cost surface near the optimum is often relatively flat and can be somewhat "noisy", increasing the likelihood that a search will become trapped in a local minimum. To combat these challenges, a different type of search technique ("implicit filtering") is used, one proven to be widely applicable for problems where the solution surface exhibits high-frequency, low-amplitude noise (Choi et al. 1999).

This simulation-optimization approach is applied to the Lower Rio Grande Valley, a region that supports an active water market (Griffin and Characklis 2002). The availability of hydrologic information and 10 years of spot lease price data make this region well suited for an exploration of water supply portfolio development. The region also exhibits characteristics typical of many water scarce Western regions, including rapidly growing municipal demand and a large agricultural sector. Results should provide general insights into the role that options and leases can play in lowering the cost of meeting water supply reliability goals. In addition, given the municipal propensity to maintain supply capacity well in excess of average usage rates, capacity that is rarely transferred back to other users, the ability to reduce the “firm” capacity maintained by municipalities could make more water available regionally in many years. It should also be noted that while firm capacity is represented as water rights in this example, the same approach could be used to develop portfolios integrating options and/or leases with hard supply infrastructure.

METHODS

An approach is developed to identify a minimum cost portfolio of rights and transfers that meets one city’s water demand with a specified reliability over a period of 12 months. The regional water supply is provided via a reservoir, with water allocated to users through a system of rights. Water can be obtained via three mechanisms:

Permanent rights – these entitle the holder to a *pro rata* share of new reservoir inflows (i.e. if the city owns 5% of regional rights it is allocated 5% of new inflows). Allocations of new inflows are made at the end of each month and the water can be used in any subsequent month. Permanent rights are transferable, but regulatory approval takes time, so the city’s volume of permanent rights is assumed to remain constant throughout the year. The price of rights (p_R) is represented as an annualized cost based on the expense associated with buying a permanent right.

Spot market leases – lease transactions can be completed at the end of each month and leased water may then be used in any subsequent month. Leasing transactions receive less regulatory scrutiny as they involve only a temporary transfer and so may be completed quickly (i.e. within a few days). Spot lease prices in each month *t* are linked to reservoir levels and described as random variables ($\hat{p}_{L_t}$).

Option contracts – option contracts provide the right to lease water at a later date and an agreed upon price. Options can be purchased just before the beginning of the year and "exercised" on a single call date (i.e. a European call option) that corresponds to the last day of a specified month (t_X.). Once an option has been exercised, the leased water can be used in any subsequent month. Options not exercised on the call date lapse and have no further value. Option prices (p_O) and exercise prices (p_X) are based on the distribution of spot lease prices ($\hat{p}_{L_t}$) in the exercise month.

Options are priced using a "risk-neutral" approach in which it is assumed impossible to make risk-free profits (Black and Scholes 1973). In other words, the expected value an option provides relative to a spot market lease, does not exceed the option's price (Hull 1999). The price of a European call option (p_O) is calculated by discounting the option's expected value on the call date back to the point at which the option is purchased, such that

$$p_O = e^{-rT} \bullet E\left[\max\left(\hat{p}_{L_t} - p_X, 0\right)\right] \quad [1]$$

where,

r = discount rate (monthly);

T = period between purchase and exercise dates (months).

The general approach to portfolio development first involves constructing a stochastic simulation that models the city's responses to changing hydrologic and market conditions. The simulation is embedded within an optimization framework which, for any given set of initial conditions, identifies the portfolio of water market transfers that minimizes expected costs while meeting constraints related to reliability and, in some cases, cost variability. The regional context is the western United States, a setting where agricultural water use generally dominates and increasing water scarcity is driven by urban expansion. As such, there are several implicit assumptions. One is that the city is a relatively small player within the regional market, and exercises no market power (i.e. it is a price taker). In addition, because the vast majority of water is used for relatively low value irrigation, it is assumed that the city can always find sufficient water available within the market to accommodate a lease or exercise transaction.

Hydrologic-Market Simulation

The simulation runs over a 12 month period, beginning on December 31st (*t* = 0), with the city holding some number of permanent water rights (N_{R_T}) and options (N_O). Initial conditions specify reservoir storage (R_0) and the amount of water the city has carried over from the previous year (N_{r_0}). In each of the following months, regional hydrologic conditions are simulated by sampling from monthly distributions of reservoir inflow, outflow and losses, with these conditions linked to both the city's water supply and the spot market price for water. This information is then combined with monthly distributions of the city's demand to make decisions regarding the purchase of leases and/or exercise of options. Multiple simulation runs for each set of initial conditions generate values for the expected annual cost of the city's portfolio, expressed as (Note: all random variables denoted by "^"),

$$\mathrm{E}\left[Annual\ Cost\right] = N_{R_T} p_R + N_O p_O + \mathrm{E}\left[N_X\right] p_X + E\left[\sum_{t=0}^{11} N_{L_t} \hat{p}_{L_t}\right] \qquad [2]$$

where,

N_{R_T} = total volume of permanent rights held by city (ac-ft);

N_O = volume of options purchased at the beginning of the year (ac-ft);

N_X = volume of exercised options (ac-ft);

N_{L_t} = volume of spot leases purchased at the end of each month (ac-ft).

Within the simulation, the following constraints apply:

$N_X \le N_O$ = the city cannot exercise more options than it buys in $t = 0$; [3]

$\sum_{i=0}^{11} N_{r_i} \le N_{R_T}$ = allocations of reservoir inflows to the city's permanent rights cannot exceed the number of rights that the city holds; [4]

$R_{Max} \ge R_t \ge R_{Min}$ = Reservoir level must stay within specified bounds related to storage capacity (R_{Max}) and minimum storage levels (R_{Min}); [5]

Standard non-negativity constraints also apply for all variables.

A series of random variables describe regional hydrologic conditions, including

$\hat{i}_t$ = historical volume of reservoir inflows for each month t;

$\hat{l}_{R_t}$ = historical volume of reservoir losses for each month t;

$\hat{o}_t$ = historical volume of reservoir outflows for each month t.

A water balance is maintained on the reservoir system throughout the simulation such that,

$$R_t = R_{t-1} + i_t - o_t - l_{R_t}\,. \tag{6}$$

From the perspective of the individual city, total reservoir storage is less important than the volume of water available to the city itself, an amount largely determined by the city's initial supply (N_{r_0}) and its share of monthly reservoir inflows (N_{r_t}). New reservoir inflows are calculated as the difference between monthly reservoir inflows and losses, multiplied by an instream loss factor (l_I), such that new inflow distributions for each month ($\hat{n}_t$) are computed as

$$\hat{n}_t = \left(\hat{i}_t - \hat{l}_t\right) \bullet \left(1 - l_I\right) \qquad [7]$$

These inflows are allocated on a pro rata basis such that the distribution of new monthly inflows accruing directly to the city ($\hat{N}_{r_t}$) is represented as

$$\hat{N}_{r_t} = \hat{n}_t \bullet \left(\frac{N_{R_T}}{\overline{N}_R}\right) \qquad [8]$$

where,

$\overline{N}_R$ = total volume of regional water rights.

The volume of water available to the city in any month is assessed at the end of the preceding month, and the method of calculation changes depending on whether it is before or after the exercise month (t_x). In months prior to t_x, the supply available to the city in the next month (S_{t+1}) includes new inflows and purchased leases, less water usage such that,

$$S_{t+1} = \sum_{i=0}^{t} N_{r_i} + \sum_{i=0}^{t-1} N_{L_i} - \sum_{i=1}^{t} u_i \, , \qquad \text{for } t = 0, 1, 2 \ldots t_X\text{–}1. \qquad [9]$$

where,

u_t = city's usage in month t.

In subsequent months, the available supply also includes exercised options, such that

$$S_{t+1} = \sum_{i=0}^{t} N_{r_i} + \sum_{i=0}^{t-1} N_{L_i} - \sum_{i=1}^{t} u_i + N_X \qquad \text{for } t = t_X, t_X+1 \ldots 11. \qquad [10]$$

The decision as to whether or not to purchase leases is the last step in each month, and the decision is based on the city's available supply, specified by [9] or [10] (neither of which include consideration of leases purchased in month *t*). The leasing decision involves consideration of both the city's available supply and the volume of new inflows it expects to have allocated to it in future months. These two values are summed to yield the city's expected water supply ($S_{E_{t+1}}$) over the remainder of the year, such that

$$S_{E_{t+1}} = S_{t+1} + \sum_{\mathrm{i=t+1}}^{11} \mathrm{E}\left[N_{r_i}\right] \qquad \text{for } t = 0, 1 \ldots 10. \qquad [11]$$

November (t = 11) inflows are considered when calculating the available supply for December, but December inflows are allocated to the following year. Therefore, December's available supply and expected supply are equal (i.e. $S_{E_{t+1}} = S_{t+1}$).

Once the city's expected water supply has been calculated, the decision is made to purchase leases and/or exercise options. This is a two part decision in which the first step involves determining whether or not to acquire water, and second involves deciding how much. Both decisions are based on the ratio of expected supply-to-expected demand, with the decision to acquire made by comparing this ratio against a threshold value (α), such that

$$\textit{if} \quad \frac{S_{E_{t+1}}}{\sum_{i=t+1}^{12} \mathrm{E}\left[\hat{d}_i\right]} \le \alpha, \qquad \textit{then,} \text{ the city will acquire water,} \quad \text{for } t = 0, 1, 2 \ldots 11 \qquad [12]$$

where,

$\hat{d}_t$ = distribution of the city's water demand during each month *t*.

The question of how much to lease and/or exercise is made by comparing the ratio of expected supply-to-expected demand with a second threshold value (β). This leads to leases (N_{L_t}) being purchased and/or options (N_X) exercised until

$$\frac{\left(N_{L_t} + N_X\right) + S_{E_{t+1}}}{\sum_{i=t+1}^{12} \mathrm{E}\left[\hat{d}_i\right]} = \beta, \quad \text{for } t = 0, 1, 2 \ldots 11 \qquad [13]$$

In all months except t_x, $N_X = 0$ and the volume of leases purchased can be represented as,

$$N_{L_t} = \beta\left(\sum_{i=t+1}^{12} \mathrm{E}\left[\hat{d}_i\right]\right) - S_{E_{t+1}}, \quad \text{for } t \neq t_X. \qquad [14]$$

During t_x, the decision process is modified such that exercising options is considered before purchasing leases. Under these conditions, the first step is to compare the exercise price (p_X) with the current spot lease price (p_{L_t}). If the lease price is less than the exercise price, the city will simply lease the volume defined in [14], however, if the exercise price is less than the lease price, the city will exercise options, with the volume to be exercised expressed as,

$$\textit{if} \quad \beta\left(\sum_{i=t+1}^{12} \mathrm{E}\left[\hat{d}_i\right]\right) - S_{E_{t+1}} \leq N_O, \quad \textit{then} \quad N_X = \beta\left(\sum_{i=t+1}^{12} \mathrm{E}\left[\hat{d}_i\right]\right) - S_{E_{t+1}}, \quad \textit{otherwise} \quad N_X = N_O. \qquad [15]$$

In the case of the latter scenario, where options alone are insufficient to satisfy [13], the city will acquire additional water via leasing, such that

$$N_{L_t} = \beta\left(\sum_{i=t+1}^{12} \mathrm{E}\left[\hat{d}_i\right]\right) - S_{E_{t+1}} - N_X, \quad \text{for } t = t_X. \qquad [16]$$

Different values of α and β can be specified for individual seasons or even individual months. In the example described later, two different parameter pairs are established, one (α_1/β_1) for the period running up to the month before options can be exercised ($t_0 \rightarrow t_X$-1) and another (α_2/β_2) for the remainder of the year. Expected supply [11] is similarly partitioned, such that it is calculated relative to t_X in months leading up to t_X, and calculated relative to the end of the year in all subsequent months.

Water is acquired just before the monthly counter changes (i.e. month t+1 becomes month t), correspondingly $S_{t+1} \rightarrow S_t$ which is then represented as,

$$S_t = \sum_{i=0}^{t-1} N_{r_i} + \sum_{i=0}^{t-1} N_{L_i} - \sum_{i=1}^{t-1} u_i, \qquad \text{for } t = 1, 2 \ldots t_X, \qquad [17]$$

or

$$S_t = \sum_{i=0}^{t-1} N_{r_i} + \sum_{i=0}^{t-1} N_{L_i} - \sum_{i=1}^{t-1} u_i + N_X \qquad \text{for } t = t_X+1, t_X+2 \ldots 12. \qquad [18]$$

Available supply is compared with a demand value (d_t) randomly sampled from monthly distributions ($\hat{d}_t$). If available supply is sufficient to meet this demand (i.e. $S_t \geq d_t$), then demand equals usage ($u_t = d_t$). If available supply is insufficient, then $u_t = S_t$ leaving a shortfall of $d_t - S_t$ and a “failure” is recorded for that month. A distinction is made between a “failure” and a “critical failure” ($S_t/d_t \le 0.6$) in order to recognize differences in severity and the measures that would be required to compensate for the shortfall. A running tally of both failures and critical failures is maintained throughout the simulation.

Once available supply and demand have been compared, the process of evaluating new allocations and lease/exercise decisions repeats monthly through the end of the year. Each annual run within this probabilistic framework represents one realization of the cost and reliability of a portfolio defined by selected values for the initial conditions ($R_0,\ N_{r_0}$) and decision variables ($N_R,\ N_O,\ \alpha_1,\ \beta_1,\ \alpha_2,\ \beta_2$). Multiple runs are made to determine a portfolio’s expected cost ([2]) and expected reliability, with the latter defined as,

$$\mathrm{E}\left[\mathrm{r_f}\right] = 1 - \left(\frac{\text{failures}}{12 \bullet Years}\right) \qquad [19]$$

where,

r_f = monthly reliability against a failure (i.e. $S_t < d_t$);

$Years$ = number of simulated years (i.e. annual runs).

A reasonable range of reliabilities might range from 0.995 (i.e. one failure every 16.7 years) to 0.98 (one failure every 4.2 years). A similar factor (r_{cf}) is used to measure the expected reliability relative to critical failures.

Multiple annual runs allow for an evaluation of the expected costs associated with each set of decision variables, but also the probability of very high costs in some years. Within the electricity and natural gas industries, a common metric used to describe the risk of high costs is the “contingent value at risk” (*CVAR*). Given a distribution of annual portfolio costs, the *CVAR* is calculated as the mean of the annual costs falling above the 95th percentile. Something akin to the CVAR is likely to play a role in a utility decisions, and this metric is used here.

The quantity of water remaining in the city's possession at year's end is also tracked. This remaining water is not assigned any value, a shortcoming that could raise concerns that a portfolio developed within this annual framework may not bear much resemblance to the type of portfolio that would minimize costs over a longer time horizon. For instance, a portfolio that consistently left the city with very little water at the end of the year could result in very high supply costs the following year. While the development of long-term portfolios is beyond the scope of this work, these issues will receive some attention in the Results section.

The methodology described above involves a supply strategy that includes rights, options and leases (Strategy C), however, it is easily modified to explore alternative strategies that include permanent rights alone (Strategy A) and permanent rights and options (Strategy B). In the case of a city relying on Strategy A, the number of rights (N_R) becomes the only decision variable. With respect to strategy B, the number of decision variables increases to four (N_R, N_O, α_2, β_2) and the decision framework for acquiring water (i.e. [12], [13] and [15]) is similar to that described above, except that the city acquires additional water via options alone, and only in the exercise month. Strategy C involves six decision variables (α_1, β_1 are added) and the entire monthly decision framework.

Optimization Framework

The simulation is linked to a search algorithm that identifies optimal values for the decision variables based on the following formulation (for Strategy C),

$$\underset{N_R, N_O, \alpha_1, \beta_1, \alpha_2, \beta_2}{\text{Minimize}} \quad Z = \mathrm{E}\left[Annual\ Cost \right] \qquad [20]$$

Such that:

$$\mathrm{E}\left[r_f \right] \geq \text{ monthly reliability threshold, } \in [0,1]; \qquad [21]$$

$$\mathrm{E}\left[r_{cf} \right] \geq \text{ monthly critical reliability threshold, } \in [0,1]. \qquad [22]$$

Some results also incorporate an additional constraint limiting cost variability, such that

$$\frac{CVAR}{\mathrm{E}\left[Annual\ Cost\right]} \leq \text{ cost risk threshold, } \in [1,\infty). \qquad [23]$$

Figure 1 illustrates a section of the optimization landscape describing expected cost as a function of permanent rights and options ($\alpha_1,\ \beta_1,\ \alpha_2,\ \beta_2$ are held constant). While the surface is relatively smooth surface when the volume of leases and exercised options is small (i.e. when a portfolio is mostly rights), as the volume of leases and exercised options increases so does the "noise". This can be problematic for many gradient-based search algorithms as they can become trapped in local minima. The amplitude of the noise can be reduced by increasing the number of simulated years, but this comes at a price in terms of computational burden.

Implicit Filtering is a finite difference optimization method in which the difference increment is varied as the optimization progresses (Kelley 1999). In this way, local minima which are artifacts of low-amplitude noise do not trap the iteration, and the noise is "implicitly filtered" out. This approach uses a finite difference gradient to compute a search direction for descent, however, unlike classical steepest descent methods in which the negative gradient (or an approximation) is used, implicit filtering uses a quasi-Newton model of the Hessian to scale the gradient, a feature that accelerates convergence in the terminal phase of the iteration. While it should be noted that implicit filtering cannot ensure convergence to a global minimum (this can only be proven for methods that undertake exhaustive efforts to asymptotically sample a dense subset of the design space), there is a rich literature describing the convergence of this class of methods, generally distinguished by the "polling" of stencil points throughout an iteration (Audet and Dennis 2003; Kelley 1999; Torczon 1997). This body of work demonstrates that, for problems involving a smooth objective function and inequality constraints, any limit point of an iteration satisfies the first order necessary conditions for optimality, and these results have been generalized to both nonsmooth (Audet and Dennis 2003; Finkel and Kelley 2004) and noisy problems (Choi and Kelley 2000; Stoneking et al. 1992).

In this application, the implementation code, IFFCO (Implicit Filtering For Constrained Optimization), uses the difference gradient stencil for more than computation of the gradient (Choi et al. 1999). The gradient-based optimization is augmented with a coordinate search using the stencil points. If the result of the coordinate search is better than the result from the descent method, IFFCO accepts the coordinate search result. The coordinate search is also used in one of the termination tests for optimization (for details see (Choi et al. 1999; Kelley 1999). IFFCO handles constraints in two ways. Simple bound constraints on variables (e.g., $N_O \geq 0$) are enforced at each iteration by setting variables that exceed the bounds to the value of the nearest bound. Indirect constraints (e.g., reliability) are handled by assigning slightly higher values to the objective function of points where the constraint is violated. These failed points are always at the edges of the stencil and they act to steer the search away from the infeasible region. IFFCO's combination of stencil based sampling and gradient-based optimization is most effective when the function to be minimized is a smooth surface with low-amplitude perturbations. Such problems are common in a number of applications, and while implicit filtering has not been applied to water resource management problems, it has been successfully employed in some related settings, including the design of groundwater remediation systems (Battermann et al. 2002; Fowler et al. 2004).

The simulation-optimization procedure includes 10,000 annual simulation runs for each set of decision variables, generating values for expected costs, reliability, critical reliability, and the CVAR which are generally reproducible to three significant figures. These parameters, as well as the α and β values, are passed to IFFCO which then guides the search of the optimization landscape. A search duration of 50 calls to the function (i.e. simulation) per decision variable was generally found to provide a resolution with respect to the expected cost and composition of minimum cost portfolios that corresponded to less than 1% and 200 ac-ft, respectively. In some cases, 50 calls were insufficient to reach this resolution, and in these instances the solution from the first 50 calls (or a close approximation) was used as a starting point and the process repeated until changes in the solution were within these tolerances.

Study Region

The U.S. side of the Lower Rio Grande Valley (LRGV) derives its water supply almost entirely from the Rio Grande, with flows managed via the Falcon and Amistad reservoirs (Figure 2). The storage in these reservoirs is strictly divided between the United States and Mexico according to the treaty of 1944 (Schoolmaster 1991), with each countries' share of storage, inflows, outflows and losses calculated as single system-wide values (Table 1). The U.S. share of new reservoir inflows is allocated to the LRGV's nearly 1000 water rights holders by the Rio Grande Watermaster's Office, which also administers transfers between rights holders.

The hydrologic data record for the system extends over the years 1970 to 2002 (Amistad dam was completed in 1968), and while there have been subtle shifts in the purpose of the diversions over that period (municipal use increased from 7% to 13% of regional total), average annual usage and monthly usage patterns have remained largely unchanged. The precipitation that produces most new reservoir inflows occurs in north central Mexico, while the vast majority of usage occurs hundreds of miles away in the LRGV, consequently reservoir inflows and outflows in the system are poorly correlated (r[1] = 0.12) and are considered independent. Chi-squared (χ^2) goodness-of-fit tests of monthly data on reservoir inflows, outflows and losses indicated that the data did not reasonably approximate any standard distribution form, so these values are sampled from monthly data lists in the simulation. New allocations to regional rights holders [7] are calculated using an instream loss factor (l_I) of 0.175, and distributed *pro rata* across the region's 1.9 million ac-ft of water rights ($\overline{N}_R$). As the number of regional rights

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[1] Spearman correlation coefficient

substantially outstrips the average volume of new inflows, each ac-ft of rights is allocated around 0.725 ac-ft of water in an average year.

The range of December (initial) reservoir storage levels (R_0) considered varies from 0.8 to 2.2 million ac-ft (MAF). The city's share of this storage at the beginning of the year (N_{r_0}) is specified as a fraction of the total rights that the city holds (f_{R_0}), such that $N_{r_0} = f_{R_0} \bullet N_{R_T}$. While it might seem logical to assume that high/low levels of R_0 and f_{R_0} would coincide, this is not necessarily the case. A substantial percentage of annual inflows occur in the Fall, so even when year end storage is below average, Fall allocations can result in a city beginning the year with a significant volume of carryover water. Three values are chosen to represent low, normal and high values for both f_{R_0} (0.1, 0.3, 0.5) and R_0 (0.8, 1.5, 2.2 MAF), and paired combinations of these values represent initial conditions for each simulation. The city's water demand is based on usage records for Brownsville, Texas, a town of 120,000 using an average of approximately 21,000 ac-ft per year (Table 1).

The vast majority (85%) of regional water use is agricultural, much of it directed toward relatively low-valued irrigation activities (e.g. cotton), and a growing municipal population (expected to double by 2050) provides substantial economic incentives for ag-to-urban water transfers. The regional water market is relatively efficient and has presided over the steady transfer of permanent rights from irrigators and urban users in recent years (Chang and Griffin 1992; Griffin 1998). Permanent transfers are almost always approved, but must navigate a regulatory process that can take over a year to complete. Leases tend to raise fewer concerns over third party impacts and are subject to a simplified approval process that is often concluded in a few days (Griffin and Characklis 2002). Lease transactions require only that the buyer and seller deliver a one page document to the Watermaster detailing their respective account numbers and the volume of water to be transferred (price information is optional). The ease of completing these transactions contributes to the high level of market activity, with an average of nearly 70,000 ac-ft of water transferred via leases each year (Watermaster's Office 2004).

All water markets exhibit idiosyncrasies. In the case of the LRGV, the most noteworthy is that current rules allow for permanent rights to be transferred between agricultural and urban users, but only allow leasing amongst similar user types (e.g. urban-to-urban), giving rise to two spot lease markets (see Characklis et al. 1999). The municipal market has fewer transactions as cities tend to hold volumes of permanent rights well in excess of average usage rates, while the agricultural lease market is much more active (1514 transactions over the period 1994-2003; average price $22.60 per ac-ft). Efforts to eliminate this prohibition on intersectoral leasing are currently being undertaken (South Central Texas Regional Water Planning Group 2000), and when this occurs it seems likely that the lower marginal value of irrigation water will lead to regional lease prices similar to those observed in the agricultural market. These simulations assume this is the case and that lease prices from the agricultural market are representative of what would be observed in ag-to-urban leases.

A brief analysis was undertaken to explore statistical correlations between spot lease prices and several hydrologic parameters (e.g., reservoir storage, inflows, outflows). The idea being that if a low reservoir level in December (when options are bought) is a strong indicator that spot market prices in May (when options are exercised) will be higher, a well informed market will incorporate consideration of this into option/exercise prices. Results suggest that the only parameter exhibiting significant explanatory power over lease prices is reservoir storage, but linear correlations between lease price and storage levels do not yield strong predictive relationships. Further analysis using the Wilcoxon two-sample test indicates (p-value <0.0001) that there are two separate populations of lease price data, one when reservoir storage is above 1.43 MAF, and another when storage is below this level. Monthly lease price data are therefore separated into two lists based on observations made when reservoir levels are either above ($\hat{p}^a_{L_t}$) or below ($\hat{p}^b_{L_t}$) this threshold (Table 1).

Consideration was given to adjusting the lease data to reflect real prices over the period 1993 to 2002. Both the *Producer price index for all farm products* (which rises from 106.3 to 111.5 over this period) and the *Texas index of prices received for farm products* (which falls from 98.0 to 93.0 over the same period) seem likely to be strong indicators of variation in the marginal benefits of irrigation water over time, but the mixed directions and small changes in these indices led to the decision to use unadjusted (nominal) lease prices. Chi-squared tests yielded little evidence that monthly lease data fit any standard distribution type, so lease prices are sampled monthly from the appropriate list.

Option contracts have been discussed in the LRGV, but are not yet actively traded. Their introduction into the market, however, would appear to be a logical step with few bureaucratic hurdles. Within the simulation, a single type of European call contract is offered, with the option purchased on December 31st (*t* = 0) and exercised on May 31st (*t* = 5), a date that falls just before the peak usage months in both the municipal and agricultural sectors. Given an initial reservoir storage (R_0), the conditional probability of May storage (R_5) being above or below 1.43 MAF can be computed, and it is assumed that the market incorporates this information into option pricing. As a result, [1] is modified such that the option price is conditional on R_0, with

$$p_{O|R_0} = e^{-r\bullet 5} \bullet P\left[R_5 \geq 1.43\text{MAF} \mid R_0\right] \bullet E\left[\max\left(\hat{p}^a_{L_5} - p_X,\, 0\right)\right] + e^{-r\bullet 5} \bullet P\left[R_5 < 1.43\text{MAF} \mid R_0\right] \bullet E\left[\max\left(\hat{p}^b_{L_5} - p_X,\, 0\right)\right]. \qquad [24]$$

The exercise price (p_X) is held constant at \$15 per ac-ft, resulting in option prices of \$13.26, \$11.36, and \$2.18 per ac-ft when initial storage levels are 0.8, 1.5, and 2.2 MAF, respectively.

The annualized price of permanent rights (p_R) is \$22.60 per ac-ft, but considering that only about 0.7 ac-ft are allocated to these rights in an average year, the effective annualized cost of water obtained via these rights is \$31.17 per ac-ft .

RESULTS

Using the least favorable set of initial conditions ($f_{R_0} = 0.1;\ R_0 = 0.8\ \text{MAF}$), minimum cost portfolios are identified for strategies A (permanent rights alone), B (rights and options) and C (rights, options and leases) (Figure 3). Several reliability levels are assessed, with reliability defined relative to the initial conditions. In other words, a portfolio providing 99.5% reliability under the least favorable conditions would translate to an even higher reliability if the same portfolio were used under better conditions. Critical failures are limited to <0.5% in all cases.

Achieving 99.5% reliability using permanent rights alone (A) requires the maintenance of just over 70,000 ac-ft of rights with an annual cost of \$1.59 million (\$MM). The volume of permanent rights is fixed throughout the year, so this cost is invariant, but reducing reliability from 99.5 to 99%, lowers expected costs by \$0.1MM (Table 2). Reducing reliability from 99 to 98% lowers annual costs by \$0.09MM, indicating that the marginal cost of reliability rises with increasing reliability. Most failures occur in December, but on average there is a substantial volume of water leftover at year's end (23,200 ac-ft).

Using strategy B, a 99.5% reliability level can be achieved with 53,000 ac-ft of permanent rights and 11,000 ac-ft of options (4900 ac-ft of which are exercised on average). The expected annual cost of this portfolio is \$1.34MM, a reduction of a little over \$0.25MM (16%) relative to strategy A. The ability to make acquisition decisions in May, when improved information is available, also leads to a significant reduction in the average volume of water remaining in the city's possession at year end (17,100 ac-ft). This not only reduces the city's expected costs, but also makes more water available to other regional users in most years.

Strategy B results in some cost variability, but the interquartile cost range (i.e. the 25^{th} to 75^{th} percentile) extends from only \$1.32MM to \$1.35MM. The CVAR is \$1.37MM, small relative to the expected value, indicating that the use of options can significantly reduce expected costs relative to sole dependence on permanent rights, while still limiting the city's exposure to large cost fluctuations. The marginal cost of reliability (\$0.1MM/percentage point from 99% to 99.5%) is approximately half of that for strategy A, but both strategies exhibit increases in marginal cost as reliability rises. The volume of permanent rights in Strategy B is driven largely by the monthly allocations required to reliably meet demand prior to May 31st when options can be exercised. In this case, if permanent rights were reduced below 53,000 ac-ft, the number of failures occurring before the city could exercise would make it impossible to maintain an overall reliability of 99.5%. With only rights and options, the city has one opportunity to augment its supply, consequently, the values for α_2 (1.67) and β_2 (1.85) must be relatively high to ensure that the 99.5% reliability goal is met (Table 2). The value of α_2 declines with lower reliability as the city allows the ratio of expected supply-to-expected demand to drop a little lower before acquiring more water. Meanwhile, β_2 rises from 1.85 to 2.15 as reliability declines suggesting that when the city does exercise options, that it will exercise slightly more. It should be noted, however, that in this case the expected costs are not very sensitive to small differences in the β_2. Once β_2 is sufficiently large to ensure that enough options are exercised to meet reliability goals, then small increases in its value only lead to a few more options being exercised and an almost imperceptible increase in expected costs. For example, in the case of 99% reliability, varying β_2 from 2.10 to 2.40 increases the volume of exercised options from 3,888 to 3,956 ac-ft and raises expected costs less than a thousand dollars. By contrast, a similar variation in α_2 would have a greater impact on expected costs as it would increase the number of acquisitions made, not just their size. Expected costs would also be more sensitive to variation in β_2 if the number of options the city holds were higher. In some situations the solution surface is quite flat in the neighborhood of the expected cost minimum, and randomness in the search path can lead to the identification of portfolios with nearly identical values for expected cost and reliability, but different α and β values. The guidelines set for the simulation and search algorithm provide a resolution that was deemed appropriate for this work, but this resolution could be increased at the cost of increased computation time.

Strategy C involves consideration of permanent rights and both types of temporary transfer (options and leases). In this case, opportunities for spot market acquisitions, in combination with the relatively high costs of permanent rights, would lead a city interested solely in minimizing expected costs to eliminate permanent rights from its portfolio. Such a strategy provides an interesting lower bound, but is unlikely to be widely adopted, so alternative portfolios are also considered:

- C1 – The city is willing to use temporary transfers to reduce its supply costs, but is concerned over the risks associated with cost variability and will not accept a portfolio for which the CVAR-to-expected costs ratio exceeds 1.10 (i.e. constraint [23] is employed);
- C2 - The city maintains 33,000 ac-ft of permanent rights, an amount that will yield a little more water than the city's average annual demand of 21,000 ac-ft in most years (although timing between supply and demand may not coincide). The city then considers the use of temporary transfers to supplement its supply, but places no limits on cost variability;
- C3 - the city maintains no permanent rights and relies entirely on temporary transfers to meet demand and places no limits on cost variability.

Limits on the CVAR-to-expected cost ratio, result in the C1 portfolio depending primarily on permanent rights (56,900 ac-ft) with a small volume of spot market leases (but no options) used to augment supply. Expected costs decline only slightly relative to strategy B, while the CVAR rises, but remains within the imposed limit. There is also a small decline in the average year-end supply. The large volume of rights ensures the city will not need to resort to the spot market between December and April, so α_1 and β_1 are not applicable. In the latter portion of the year the α_2 value indicates that the increased acquisition opportunities allow the city to be less risk averse than with strategy B, waiting until the expected supply-to-expected demand ratio drops to 1.30 instead of 1.67 before acquiring water (β_2 drops to 1.31 indicating that acquisitions are also smaller). Decreasing α_2 and β_2 serves to lower reliability, with the marginal cost of reliability remaining relatively similar to that of strategy B from 99.5 to 99%.

Expected cost drops significantly using strategy C2 ($0.92MM). This is accompanied by a CVAR of $1.10MM which is substantially less than that observed for strategies A, B or C1, but still pushes the CVAR-to-expected cost ratio up to 1.20. There is also a considerable decrease in the average volume of water leftover at year's end (7,100 ac-ft). Options again play no role as the greater flexibility of the spot market (and lack of concern over the CVAR) makes leasing a less expensive means of meeting reliability constraints. The increased flexibility of the spot market also results in lower marginal costs for reliability. The expected supply-to-expected demand ratio will always be quite low at the beginning of the year given the unfavorable initial conditions, so small variations in α_1 have little impact on reliability (i.e. the city will always buy in December unless α_1 were significantly lower), but small changes in acquisition size (β_1) do lower reliability. In this case, the relatively large acquisitions made in December provide enough water so that post-April acquisitions are smaller (i.e. $\beta_2 < 1$) and made when the supply-to demand ratio is quite low (i.e. $\alpha_2 < 1$), thus they serve as a means of subtly adjusting supply in the latter part of the year.

The expected cost of meeting 99.5% reliability through strategy C3 declines to $0.58MM with a portfolio that relies entirely on spot market leases, a dependence that increases the CVAR-to-expected cost ratio to 2.0. The city begins the year with no permanent rights and will need to buy water immediately, so α_1 values are meaningless. The high β_1 (2.56) points to a large acquisition in t = 0, large enough that only some subtle adjustments to supply are required in the late summer and fall to meet reliability objectives in most years. In this case, the size of the December acquisition and the fact that it is always the same size (for a given set of initial conditions), means that most of the variability in portfolio cost is due to price volatility, not differences in the timing or magnitude of acquisitions. This leads to an interquartile range that is narrower than might be expected. The range is still considerably wider than that of C2 in relative terms, since C2's expected costs are 60% higher, but in C3 a much larger fraction of annual demand is met with this initial acquisition. Very dry years still result in large late-year acquisitions and lease prices in December can be high in some years, both of which contribute to the large CVAR, but in at least half the years, annual costs will fall within +/-12% of the expected value.

When considering the practicality of each strategy, it seems clear that the realities associated with managing a utility make it unlikely that strategy C3 would be widely adopted. Furthermore, the increase in cost variability realized in switching from C1 to C2, would seem a small price to pay for the significant reduction in expected costs. This leaves strategies B and C2 as perhaps the most attractive alternatives to sole reliance on permanent rights, given that both significantly reduce expected costs while limiting a city's exposure to wide cost swings. As a result, these two strategies receive further analysis under a broader range of initial conditions. Portfolios are most sensitive to changes in the initial water supply (a function of f_{R_0}). Changes in initial reservoir storage (R_0) have little impact on portfolio composition, but do lower expected cost slightly as the price of options and leases declines with increasing storage. Exploring portfolio changes under alternative initial conditions provides some illustrative context for the earlier results, but is also useful in making rough assessments regarding how annual portfolios can be translated into longer term supply strategies.

Figure 4 describes minimum cost portfolios (99.5% reliable) developed using strategies B and C2 under more favorable initial conditions in which the city's volume of carryover water from the previous year is higher. More water to start the year naturally results in a reduction in the expected costs and supply required to meet reliability goals, but it is important to note that the assumption that permanent rights take some time to acquire plays a considerable role in determining which type of strategy to pursue over multiple years. For example, if pursuing strategy B, a city would have no choice but to acquire and hold approximately 53,000 ac-ft of rights in order to meet its reliability goals in unfavorable years (f_{R_0} = 0.1). This additional firm capacity results in much higher costs, but also a considerable supply of water left over in most years (17,000 ac-ft). In the case where f_{R_0} = 0.3, the city starts the year with roughly the same amount (f_{R_0} x permanent rights = 0.3 x 26,000 = 7,800 ac-ft) it can expect to have remaining at the end of the year (8,000 ac-ft). This suggests that if every year were an average year in terms of inflows, holding 26,000 ac-ft of permanent rights and 6,500 ac-ft of options would be a sustainable long-term portfolio. However, when options are considered the only means of acquiring water within the year, the single exercise date is limiting and the city must hold many more rights as security against dry years (when f_{R_0} will likely be below 0.3). Expanding consideration of acquisition types to include leasing (i.e. strategy C2) can significantly reduce the need for large holdings of permanent rights. In this case, the city keeps a constant volume of only 33,000 ac-ft of rights, enough to meet demand whenever f_{R_0} ≥ 0.3 with only a few hundred ac-ft of leases. Leasing increases to an average of around 7,000 ac-ft when f_{R_0} = 0.1, and no leasing is required when f_{R_0} = 0.5. In addition, similar to strategy B, this strategy results in roughly equivalent levels of year-end supply (8,000 ac-ft) and initial supply (9,900 ac-ft) in average years, implying a reasonable level of stability in most years.

Changes in initial reservoir storage (R_0) from 0.8 to 1.5 to 2.2. MAF, holding f_{R_0} constant at 0.1, reduces the cost of leases and options, but lowers expected portfolio costs only slightly from \$0.92 to \$0.87 to \$0.85MM, respectively.

Strategy C2 could be further refined by introducing options and varying the relative distribution of leases and options as a means of "fine tuning" the tradeoffs between expected costs and cost variability. Besides limiting cost variability, options can also provide some practical advantages in multi-year planning as they provide an opportunity for long-term revolving contracts. These might involve the city making an annual payment for a specified volume of options each year. Such a contract could limit the city's exposure to spot market volatility, while still allowing some access to the flexibility the spot market provides. Figure 5 describes a range of variations on strategy C2, each containing 33,000 ac-ft of rights and meeting 99.5% reliability through various combinations of leases and purchased options. Under the least favorable initial conditions, a city could reduce its expected number of leases 25% (from 6860 to 5270 ac-ft) with a contract for 4000 options, resulting in a portfolio with expected costs only slightly higher ($0.05MM) than one without options, but with a lower CVAR (more than 4000 ac-ft of options does little other than raise expected costs). As part of the long-term contract, the city would be committed to the option payment during years in which conditions were more favorable, but it would be less vulnerable to large swings in lease price during other years. While this is a subjective assessment of potential multi-year strategies, it does suggest that some variation of C2 might be an attractive starting point for a city seeking to lower cost long-term water supply costs. Annual increases in permanent rights could be made to keep base capacity in line with demand growth, while long-term option contracts could reduce the need for leasing while providing added security and insulation from large swings in spot market prices. The implementation of such a strategy would not only lower supply costs, but also reduce the quantity of water the city maintains in most years, a feature that could have significant benefits in water scarce regions.

CONCLUSIONS

Most cities with access to water markets currently rely on permanent rights alone to meet demand. The results of this work suggest that expanding a city's water supply portfolio to include options and/or leases could significantly lower expected costs while maintaining high levels of reliability. Considerable reductions in expected cost can be realized through the introduction of options alone, but the use of spot market leases can cut costs even further (by up to 65%). While it is unlikely many cities would undertake a supply strategy that relied entirely (or even primarily) on temporary transfers, more conservative approaches in which leases and options supplement a substantial base capacity of permanent rights could still reduce expected costs on the order of 40%.

With respect to the solution technique, implicit filtering proves to be an effective search method for the noisy solution (i.e. expected cost) surface generated in this type of water resource problem, and it appears likely that this method may have broader applications within the field of water resource management. The IFFCO algorithm provided repeatable solutions for minimum expected cost and reliability that were accurate to three significant figures. It should be noted, however, that in some cases small solution surface gradients in the neighborhood of the cost minimum, and insensitivity of expected cost and reliability values to the decision rules, made it difficult to identify unique values for α and β.

The substantial cost saving potential of a more diversified approach to water supply management will become increasingly attractive as water demand and the costs of supply development continue to grow. As such, these results may provide useful information to cities seeking to develop more cost effective supply strategies. From a regulatory perspective, it should also be noted that leasing and option contracts require more robust monitoring and enforcement institutions than those required to oversee permanent transfers. Thus, the estimated reduction in urban water supply costs could be used to argue for investment in these improved capabilities as well.

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FIGURE CAPTIONS

Figure 1: Optimization landscape (constant values for α_1/β_1 and α_2/β_2)

Figure 2: Lower Rio Grande Region

Figure 3: Minimum cost portfolios for different strategies (f_{R_0} = 0.1; R_0 = 0.8 MAF)

Figure 4: Minimum cost portfolios using alternative initial conditions

Figure 5: Impact of varying the distribution of leases and options on expected cost and CVAR-to-expected cost ratio (f_{R_0} = 0.1; R_0 = 0.8 MAF)

Table 1. Simulation Data Summary

	Mo.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reservoir Inflows (i_t) (x1000 AF)	**Mean**	89.6	88.5	91.0	100.2	142.2	159.0	159.8	195.8	246.8	203.2	106.3	87.5
	Max	177.8	213.8	156.2	372.4	450.4	410.3	837.1	1095.9	1660.7	748.7	329.5	180.5
	Min	18.3	39.3	44.8	33.0	3.4	51.6	36.3	44.1	58.6	48.7	43.5	36.0
Reservoir Outflow (o_t) (x1000 AF)	**Mean**	82.3	70.0	94.5	143.2	159.6	152.5	124.7	132.8	97.4	100.6	61.7	59.5
	Max	165.4	175.2	197.8	253.9	345.0	336.5	224.7	739.3	535.0	566.1	157.7	220.3
	Min	13.6	22.4	24.6	6.8	32.7	19.6	19.4	25.7	13.8	0.5	11.0	21.8
Reservoir Losses (l_t) (x1000 AF)	**Mean**	17.4	21.5	34.3	41.9	46.0	52.6	57.7	55.0	40.8	33.0	22.4	16.9
	Max	25.9	36.4	52.1	59.6	70.6	76.5	86.9	86.8	62.8	51.7	33.3	28.3
	Min	7.7	10.9	19.6	19.5	21.8	24.1	28.1	28.5	20.3	15.0	11.6	9.2
Spot Lease Prices (p_{Lt}^{a}) ($/ac-ft)[a]	**Mean**	17.0	17.4	16.8	14.6	16.2	16.7	15.2	12.7	15.8	13.8	14.4	16.3
	Max	25.0	30.0	45.0	35.0	30.0	35.0	25.0	20.0	25.0	20.0	20.0	25.0
	Min	10.0	10.0	7.2	10.0	10.0	10.0	10.0	10.0	10.0	10.0	11.0	10.0
Spot Lease Prices (p_{Lt}^{b}) ($/ac-ft)[a]	**Mean**	27.9	28.5	27.6	26.2	28.0	25.3	23.4	23.5	26.7	25.0	24.9	24.4
	Max	50.0	55.0	50.0	55.0	60.0	50.0	75.0	60.0	55.0	50.0	50.0	55.0
	Min	6.8	7.2	7.2	7.2	7.0	7.0	7.0	7.0	6.8	7.2	6.8	6.8
Demand (d_t) (ac-ft)	**Mean**	1569	1457	1681	1714	1919	1957	2073	2075	1692	1639	1547	1572
	St.Dev	178.9	195.9	179.7	270	376	383.6	349.6	283.8	299	185.5	193.6	135

Inflow, Outflow and Loss data reflects the years 1970-2002 (IBWC 2004)

[a]Spot lease prices reflect the years 1994-2003 (n = 1514) (Watermaster's Office 2004)

Table 2: Minimum Cost Portfolios*

Reliability	Strategy	Expected Cost *$MM*	CVAR *$MM*	α_1	β_1	α_2	β_2	Expected year-end supply *ac-ft x1000*
	A	1.59						23.2
	B	1.34	1.37			1.67	1.85	17.1
99.5%	C1	1.30	1.41			1.30	1.31	15.6
	C2	0.92	1.10	1.56	1.77	0.93	1.04	7.1
	C3	0.58	1.16		2.56	0.97	1.09	2.4
	A	1.49						20.4
	B	1.30	1.31			1.48	2.10	15.3
99%	C1	1.25	1.38			1.20	1.28	14.1
	C2	0.91	1.07	1.48	1.74	0.90	0.93	6.5
	C3	0.57	1.16		2.50	0.96	1.04	2.1
	A	1.40						17.9
	B	1.23	1.25			1.33	2.15	13.5
98%	C1	1.22	1.35			1.20	1.23	13.4
	C2	0.90	1.06	1.62	1.69	0.70	0.79	6.1
	C3	0.55	1.09		2.32	0.75	1.07	1.8

*All portfolios assume an initial reservoir storage (R_0) of 0.8 MAF and an $f_{R_0} = 0.1$

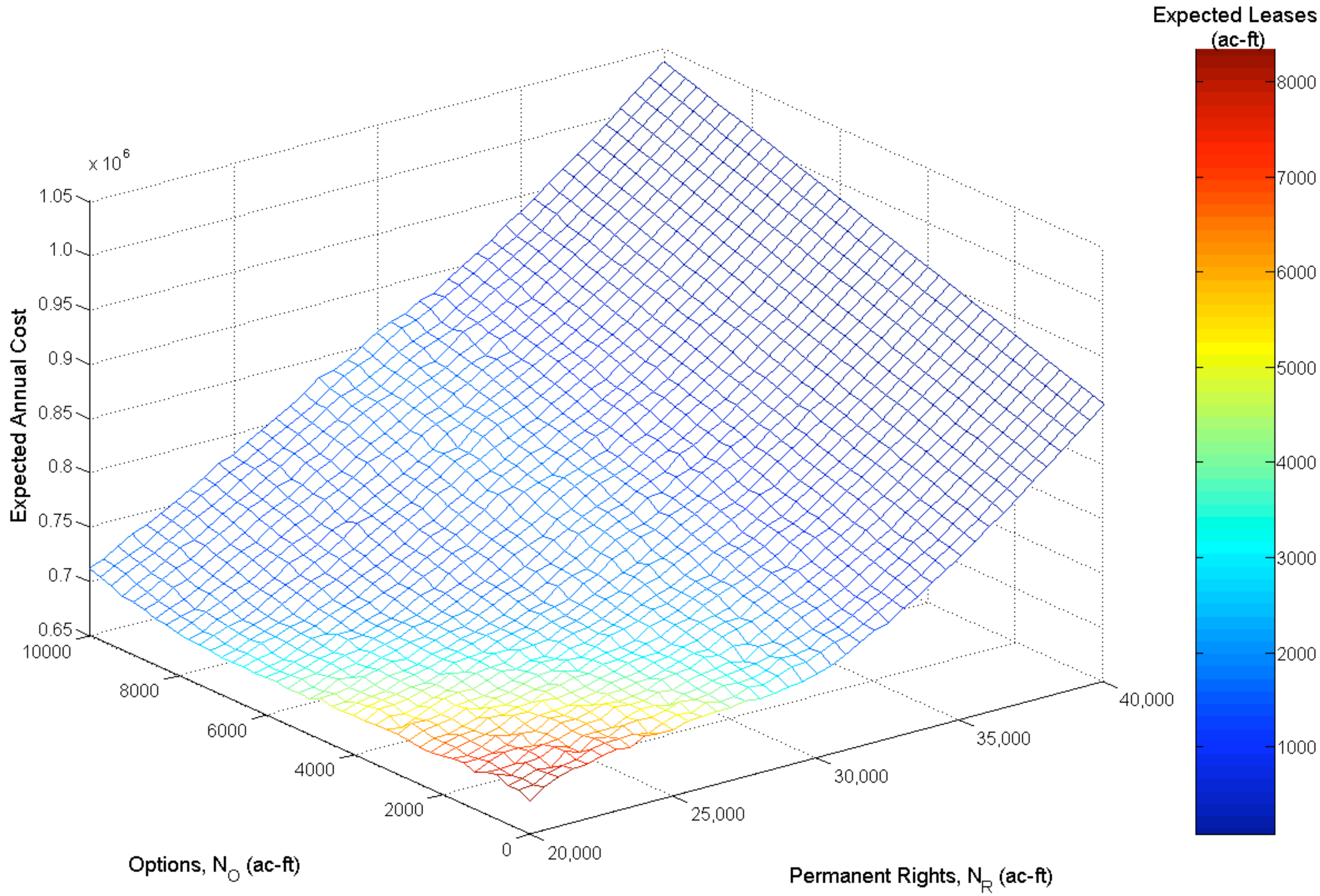


Figure 1: Optimization landscape with constant threshold values: α_1 = 1.10; β_1 = 1.30; α_2 = 0.85; β_2 = 1.10

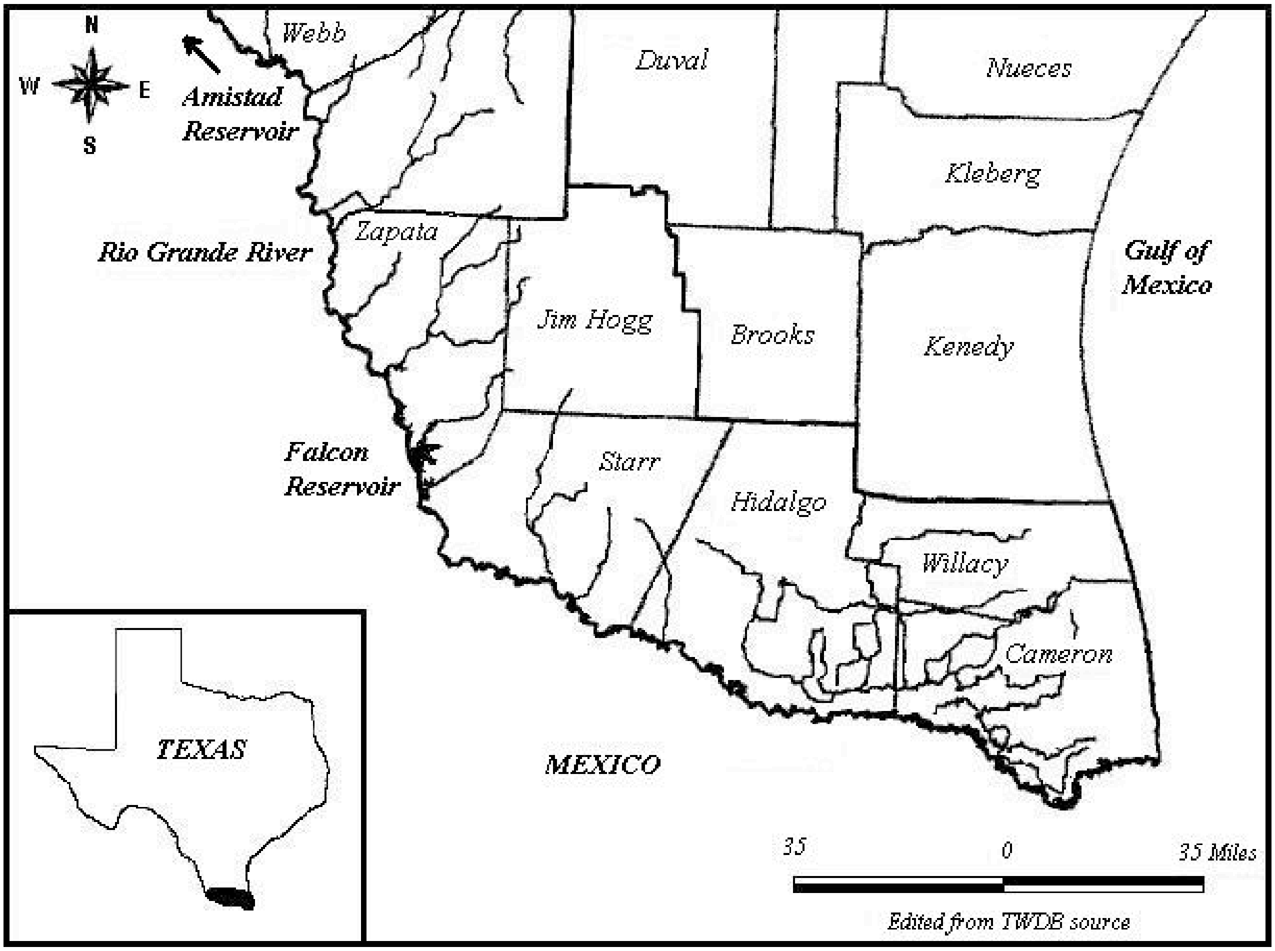
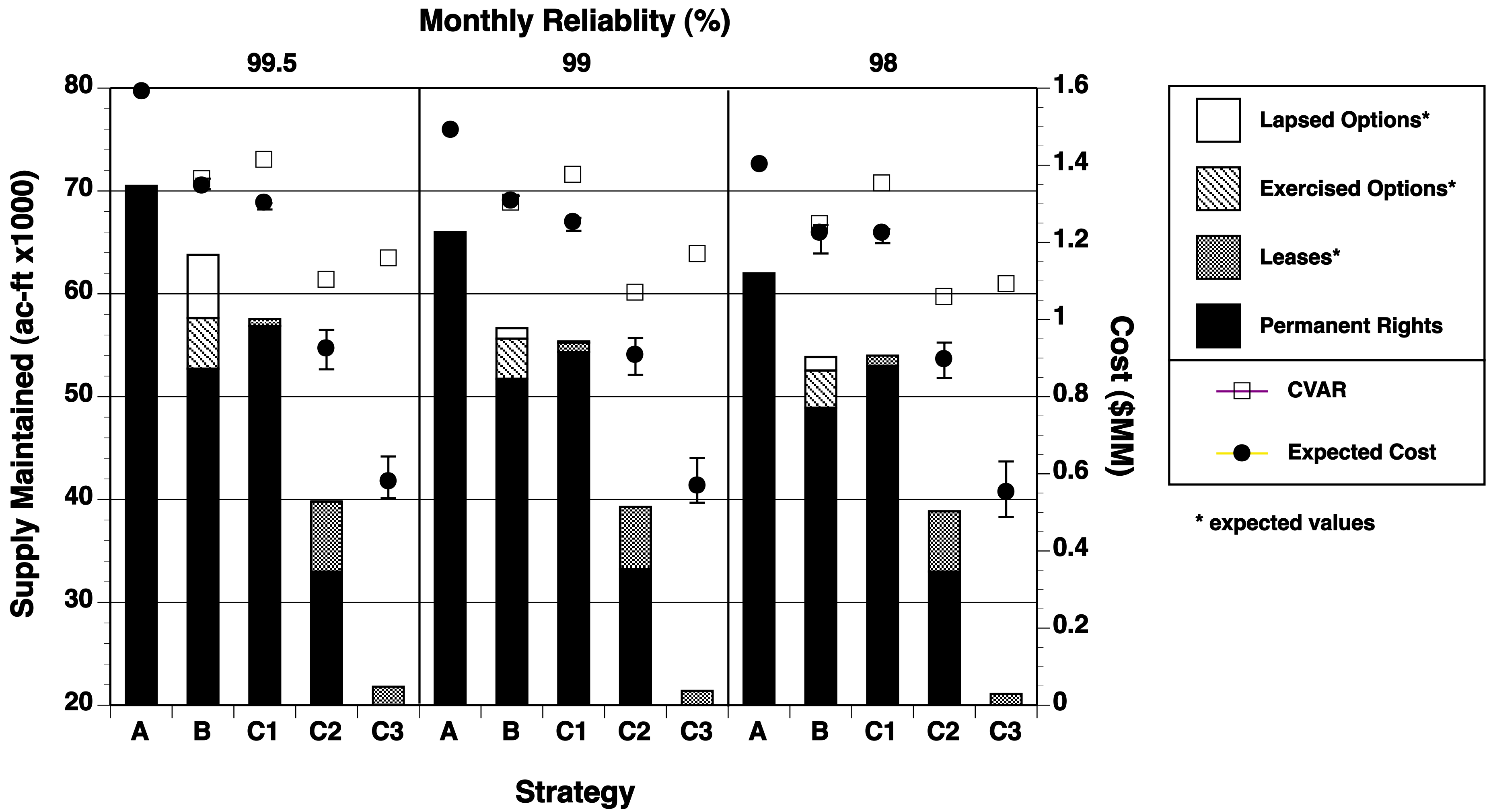
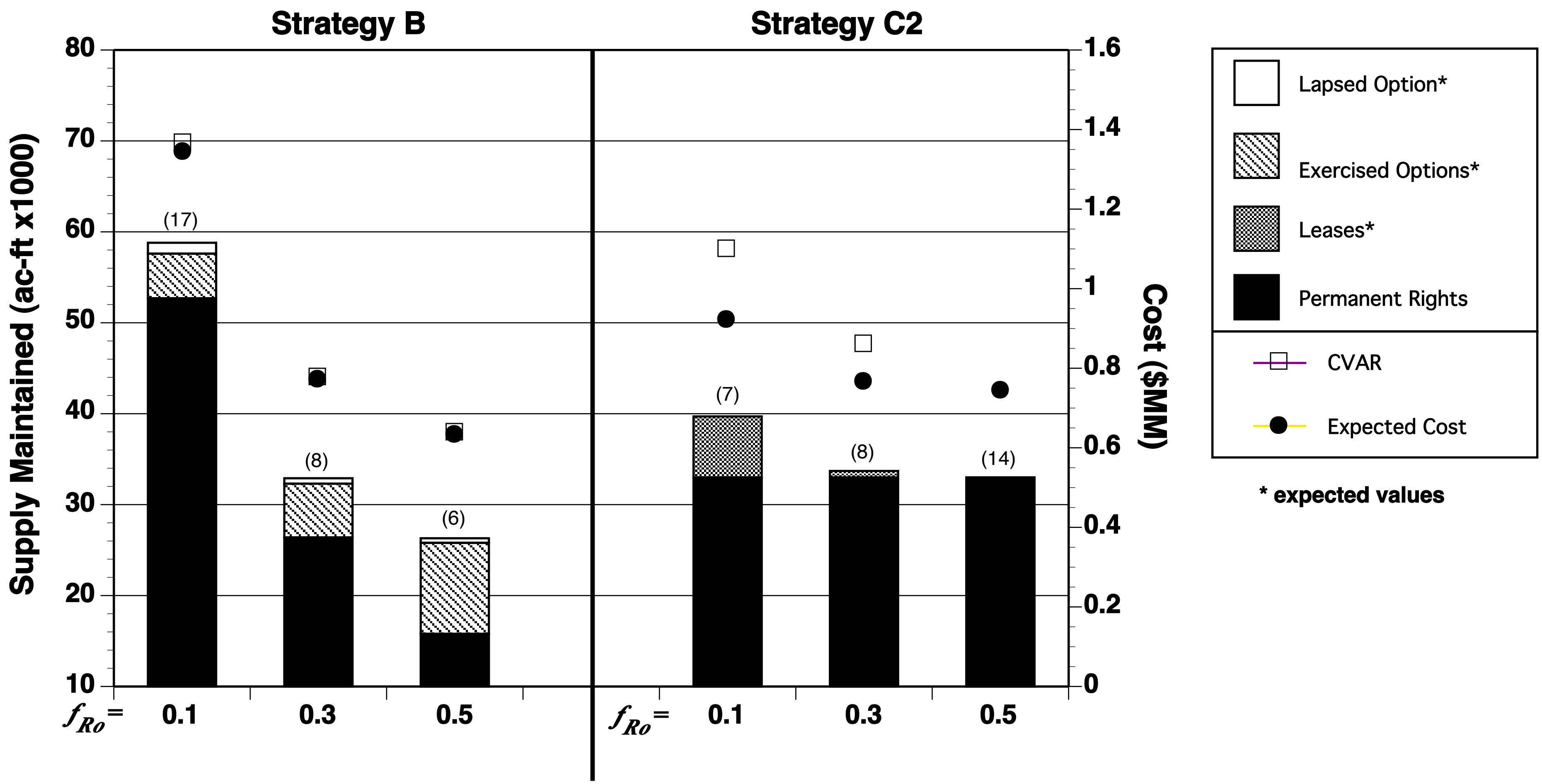


Figure 2 Lower Rio Grande Region



Note: error bars represent the 25th and 75th percentiles

Figure 3



R_o = 0.8 MAF

( ) = Expected Year-end Supply (ac-ft x1000)

Figure 4

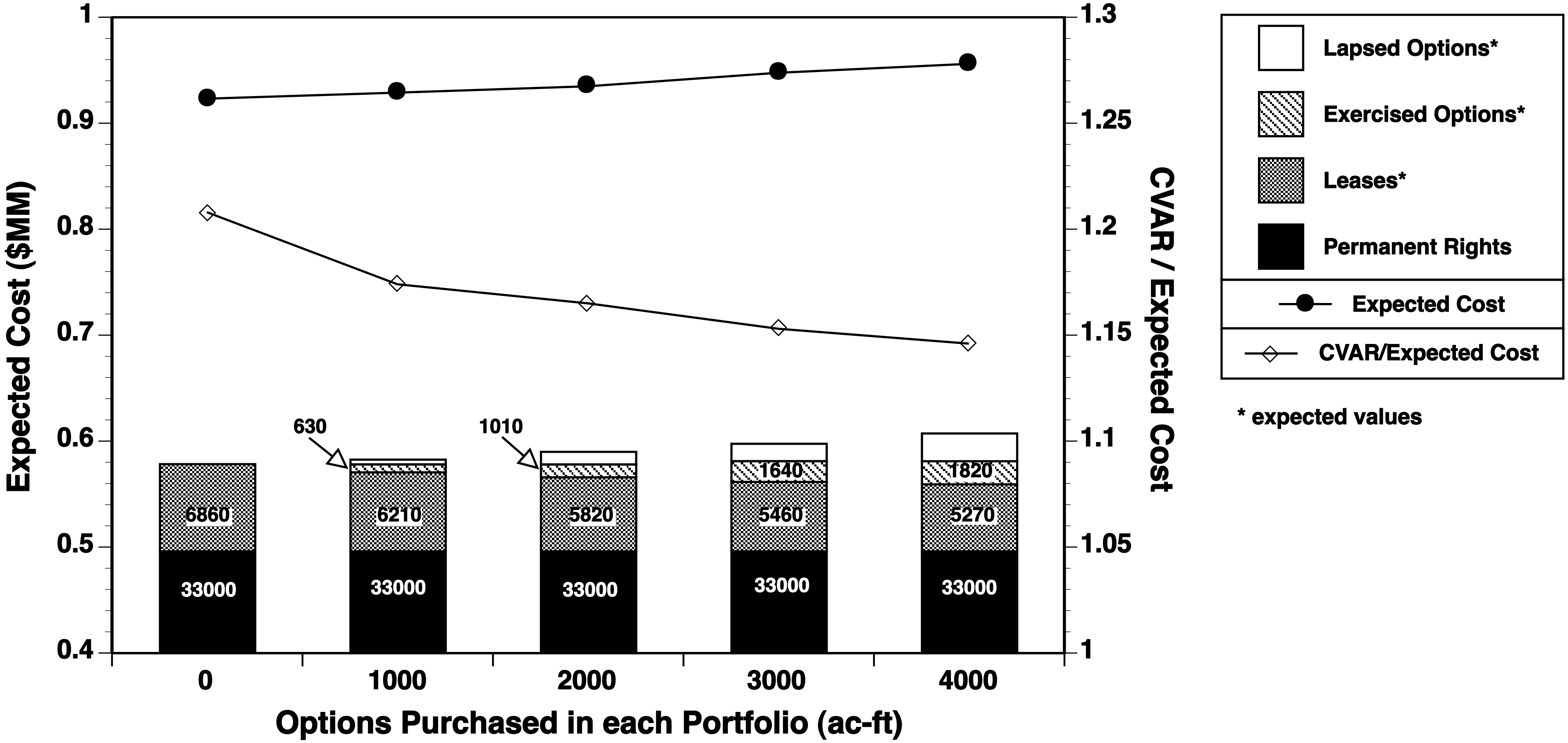

Lapsed Options*
Exercised Options*
Leases*
Permanent Rights
Expected Cost
CVAR/Expected Cost
* expected values
Expected Cost ($MM)
CVAR / Expected Cost
Options Purchased in each Portfolio (ac-ft)
0
1000
2000
3000
4000
1
0.9
0.8
0.7
0.6
0.5
0.4
1.3
1.25
1.2
1.15
1.1
1.05
1
630
1010
1640
1820
6860
6210
5820
5460
5270
33000
33000
33000
33000
33000

Figure 5