Developing portfolios of water supply transfers

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[1] 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 paper combines a hydrologic—water market simulation with an optimization approach to identify portfolios of permanent, options, and leases that minimize the 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 temporary transfers can reduce expected water supply costs substantially, while still maintaining high reliability. Also evaluated are trade-offs between expected costs and cost variability that occur with variation in a portfolio’s distribution of rights, options, and leases.


1. Introduction

[2] Rising water demand and concerns over scarcity have driven more regions to explore market-based approaches to water resource management [Anderson and Hill, 1997; Easter et al., 1998; National Research Council, 2001]. Nonetheless, many water markets remain relatively unsophisticated, with transactions revolving primarily around permanent transfers or multiyear leases. While several studies have shown that these types of transfers encourage long-term allocation efficiency [Brookshire et al., 2004; Chang and Griffin, 1992; Colby et al., 1993; Griffin and Baudou, 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 cost-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, and consequently some markets are beginning to support a more sophisticated menu of temporary transfers [Howitt, 1998]. This has resulted in an increasing number of researchers investigating 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; Jerch, 1997; McCarl et al., 1999; Michelsen and Young, 1993; Villinski, 2004; Watters, 1995].

[3] 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 [Lund and Israel, 1995b]. 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.

[4] Several previous studies have used either linear or stochastic programming techniques to identify combinations of supply alternatives (e.g., infrastructure, transfers, and conservation) that minimize the expected costs of meeting urban water demand [Jenkins and Lund, 2000; Lund and Israel, 1995a; 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 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 (3–6 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 behavior 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 or exercise. These rules are optimized to provide a decision-making framework for arriving at a least cost solution using information as it becomes available throughout the year.

Uncertainty with respect to spot market prices is also a concern when developing portfolios that include temporary transfers. In this work, spot lease prices are represented as distributions and this information is used to price options in a risk-neutral manner consistent with financial theory [Black and Scholes, 1973; Hull, 1999]. This approach involves consideration of the expected value of water rights, a parameter that has been estimated as a function of various factors in previous research [Michelsen et al., 2000], but which in this work is computed using actual distributions of spot market lease data. While probabilistic approaches to option valuation have received some attention in the water literature [Gómez Ramos and Garrido, 2004], issues related to cost variability and trade-offs between expected cost and cost variability remain largely unexplored. This is an important issue, 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. The role of cost variability in water supply decisions has received some consideration in past work. Watkins and McKinney [1999] describe an elegant approach that incorporates consideration of both expected supply costs and their variance when identifying an optimal solution (all scenarios involve 100% reliable supplies); however, their approach assumes a symmetrically distributed objective function (essentially cost). This symmetry may not exist 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 decision-making.

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 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 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, capacity that is rarely transferred back to other users, the ability to reduce the number of permanent rights maintained by municipalities could make more water available regionally in many years.

2. 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 the following three mechanisms:

- The first is permanent rights. These entitle the holder to a pro rata share of reservoir inflows (after correcting for losses), such that a city owning 5% of regional rights is allocated 5% of inflows. Allocations 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 constant throughout the year. Their price ($p_t$) is represented as an annualized cost based on purchase price.

- The second mechanism is 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 ($p_t^L$).

- The third mechanism is 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 \((t_k)\). 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 \((p_L)\) in the exercise month.

Options are priced using a “risk-neutral” approach in which it is assumed possible 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, with the expected value based on the difference between the exercise price and spot lease price, or zero, whichever is larger (expression in brackets), such that

\[
p_O = e^{-rT}E[\max(p_L - p_X, 0)],
\]

where \(r\) is the discount rate (monthly) and \(T\) is the 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 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. It is worth noting that while the assumptions related to the unlimited availability of spot market water and risk-neutral pricing provide a reasonable basis for this analysis, their use may have implications for results, and these will be discussed in later sections.

### 2.1. Hydrologic-Market Simulation

The simulation runs over a 12-month period, beginning on 31 December \((t = 0)\), with the city holding some number of permanent water rights \((N_{R_p})\) and options \((N_{R_o})\). Initial conditions specify reservoir storage \((R_0)\) and the amount of water the city has carried over from the previous year \((N_{R_r})\). In each of the following months, regional hydrologic conditions are simulated using data sets describing monthly 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 (random variables are denoted by the circumflex)

\[
E[\text{annual cost}] = N_{R_p}p_R + N_{R_o}p_O + E[N_X]p_X + E \left[ \sum_{t=0}^{11} N_L \hat{p}_L \right],
\]

where

\[
N_{R_p} = \text{total volume of permanent rights held by city (ac ft)};
\]

\[
N_{R_o} = \text{volume of options purchased at the beginning of the year (ac ft)};
\]

\[
N_X = \text{volume of exercised options (ac ft)};
\]

\[
N_L = \text{volume of spot leases purchased at the end of each month (ac ft)}.
\]

Within the simulation, the following constraints apply:

\[
N_X \leq N_{R_o} = \text{the city cannot exercise more options than it buys in t = 0};
\]

\[
\sum_{t=0}^{11} N_L \leq N_{R_r} = \text{allocations of reservoir inflows to the city’s permanent rights cannot exceed the number of rights that the city holds};
\]

\[
R_{\text{max}} \geq R_t \geq R_{\text{min}} = \text{reservoir level must stay within specified bounds related to storage capacity}(R_{\text{max}}) \text{ and minimum storage levels}(R_{\text{min}}).
\]

Non-negativity constraints also apply for all variables.

A series of variables are used to describe regional hydrologic conditions, including \(i_t = \text{volume of reservoir inflows for each month } t\); \(l_R = \text{volume of reservoir losses for each month } t\); and \(o_t = \text{volume of reservoir outflows}\) (including spillage) for each month \(t\).

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

\[
R_t = R_{t-1} + i_t - o_t - l_R.
\]

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 \((N_{R_r})\) and its share of monthly reservoir inflows \((N_r)\). Reservoir inflows available for allocation are calculated as the difference between monthly inflows and losses, multiplied by an in-stream loss factor \((l_t \in [0,1])\), which accounts for losses incurred between the reservoir and user (which in this case is assessed prior to allocation). Inflows available for allocation to rights holders in each month \(n_t\) are computed as

\[
n_t = (i_t - l_t)(1 - l_t).
\]

These inflows are allocated on a pro rata basis such that the fraction of monthly inflows allocated directly to the city \((N_{R_r})\) is represented as

\[
N_{R_r} = n_t \left( \frac{N_{R_r}}{\bar{N}_{R_r}} \right).
\]

where \(\bar{N}_{R_r} = \text{total volume of regional water rights}\).
The total 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 cumulative inflows and purchased leases, less water usage such that

\[
S_{t+1} = \sum_{i=0}^{t} N_i + \sum_{i=1}^{t-1} N_{ti} - \sum_{i=1}^{t} u_t, \quad \text{for } t = 0, 1, 2 \ldots t_x - 1. \tag{9}
\]

where \(u_t\) = city’s usage in month \(t\).

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

\[
S_{t+1} = \sum_{i=0}^{t} N_i + \sum_{i=1}^{t-1} N_{ti} - \sum_{i=1}^{t-1} u_t + N_X \quad \text{for } t = t_x, t_x + 1 \ldots 11. \tag{10}
\]

The decision of 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 monthly inflows it expects to have allocated to it over the remainder of the year (calculated on the basis of historical records). 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

\[
S_{E_{t+1}} = S_{t+1} + \sum_{i=1}^{11} E[N_i] \quad \text{for } t = 0, 1 \ldots 10. \tag{11}
\]

where \(N_i\) = distribution of inflows allocated to the city in each month \(t\).

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 the 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 specified threshold value \((\alpha)\), such that if

\[
\frac{S_{E_{t+1}}}{\sum_{i=1}^{12} E[d_i]} \leq \alpha, \quad \text{then the city will acquire water, for } t = 0, 1, 2 \ldots 11, \tag{12}
\]

where \(d_i\) = 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 specified threshold value \((\beta)\). This leads to leases \((N_L)\) being purchased and/or options \((N_X)\) exercised until

\[
\left( N_L + N_X \right) + S_{E_{t+1}} = \beta, \quad \text{for } t = 0, 1, 2 \ldots 11. \tag{13}
\]

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

\[
N_L = \beta \left( \sum_{i=1}^{12} E[d_i] \right) - S_{E_{t+1}}, \quad \text{for } t \neq t_x. \tag{14}
\]

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 \((p_{e_x})\) with the current spot lease price \((p_{L_x})\). If the lease price is less than the exercise price, the city will simply lease the volume defined in (14). If, however, the exercise price is less than the lease price, the city will exercise options, with the volume to be exercised expressed as follows:

\[
\text{If } \beta \left( \sum_{i=1}^{12} E[d_i] \right) - S_{E_{t+1}} \leq N_O, \quad \text{then } N_X = \beta \left( \sum_{i=1}^{12} E[d_i] \right) - S_{E_{t+1}}, \tag{15}
\]

\[
\text{otherwise } N_X = N_O \text{ for } t = t_x.
\]

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

\[
N_L = \beta \left( \sum_{i=1}^{12} E[d_i] \right) - S_{E_{t+1}} - N_X, \quad \text{for } t = t_x. \tag{16}
\]

Different \(\alpha\) and \(\beta\) variables can be specified for individual seasons or even individual months. In the example described later, two different parameter pairs are established, one \((\alpha_1/\beta_1)\) for the period running up to the month before options can be exercised \((t_0 \rightarrow t_x - 1)\) and another \((\alpha_2/\beta_2)\) 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. Optimal values for \(\alpha\) and \(\beta\), those that lead to a minimum expected cost portfolio that meets reliability constraints, are determined as part of the optimization routine (see next section).

The choice to link decision rules to the ratio of expected supply to expected demand was based on the ability to use this value in determining both when and how much water to acquire. Alternative decision rules could have been based on the probability of shortfall, or perhaps even linked to a threshold value for the expected benefits loss that would accrue as a result of a shortfall. These types of rules may be expressed in terms more intuitive to utility personnel and/or planners (and might be explored in future work), but their use would have necessitated additional
calculations to answer both the “when” and “how much” questions.

[25] 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

\[
S_t = \sum_{i=0}^{t-1} N_f + \sum_{i=0}^{t-1} N_c - \sum_{i=1}^{t-1} u_t, \quad \text{for } t = 1, 2 \ldots t_N.
\]  

(17)

or

\[
S_t = \sum_{i=0}^{t-1} N_f + \sum_{i=0}^{t-1} N_c - \sum_{i=1}^{t-1} u_t + N_f^t,
\]

for \( t = t_N + 1, t_N + 2 \ldots 12 \).

(18)

Available supply (\( S_t \)) is compared with a demand value (\( d_t \)) obtained by either randomly sampling a monthly distribution or selecting from a monthly time series. 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” (\( S_t/d_t \leq 0.6 \)) 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.

[26] 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 conditions (\( R_0, N_r, \) and decision variables \( N_f, N_c, \alpha_1, \beta_1, \alpha_2, \beta_2 \)). Multiple runs are made to determine a portfolio’s expected cost (equation (2)) and expected reliability, with the latter defined as

\[
E[r_f] = 1 - \frac{\text{failures}}{12 \text{ years}},
\]

(19)

where \( r_f \) is monthly reliability against a failure and years is the number of simulated years (i.e., annual runs).

[27] A reasonable span of monthly 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 \( (r_f) \) is used to measure the expected reliability relative to critical failures.

[28] Multiple annual runs also allow for evaluation of the probability of very high annual costs. 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 costs, the CVAR represents the mean of the annual costs falling above the 95th percentile. Something akin to the CVAR is likely to play a role in utility decisions, and this metric is used here.

[29] 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 (this does not actually tend to be the case, however). While the development of long-term portfolios is beyond the scope of this work, these issues will receive some attention in the results section.

[30] 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 \( (N_R, N_O, \alpha_2, \beta_2) \) and the decision framework for acquiring water (i.e., equations (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 \( (\alpha_1, \beta_1) \) are added and the entire monthly decision framework described above.

2.2. Optimization Framework

[31] The simulation is linked to a search algorithm that identifies optimal values for the decision variables based on the following formulation (for strategy C):

\[
\text{Minimize } Z = E[\text{annual cost}] \quad (20)
\]

such that

\[
E[r_f] \geq \text{monthly reliability threshold, } \in [0, 1];
\]

(21)

\[
E[r_{cf}] \geq \text{monthly critical reliability threshold, } \in [0, 1].
\]

(22)

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

\[
\frac{\text{CVAR}}{E[\text{annual cost}]} \leq \text{cost risk threshold, } \in [1, \infty).
\]

(23)

[32] Figure 1 illustrates a section of the optimization landscape describing expected cost as a function of the number of permanent rights and options \( (\alpha_1, \beta_1, \alpha_2, \beta_2 \) held constant). While the surface is relatively smooth 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.

[33] Implicit filtering is a finite difference search method in which the difference increment (i.e., the size of the finite difference stencil) 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 is in contrast to methods which explicitly try to filter out high-frequency components of the objective function [Moré and Wu, 1997; Kostrowicki and Piela, 1991]; such methods are designed for problems with high-amplitude high-frequency terms and should be thought of as global optimization algorithms. Implicit filtering is not a global optimization method, and is designed to efficiently solve problems, such as those presented in this paper, which have noisy but not violently oscillatory optimization landscapes (see Figure 1). Methods such as steepest descent, which are based on gradients, can be trapped in the small-scale local minima that noisy surfaces exhibit, and may fail if this results in an optimization surface that is not differentiable. In this problem, as in many others, the noise results from using an expected value (cost) as the objective function. The frequency and amplitude of the noise increases with greater use of leases and exercised options (probabilistic variables) and decreases with the number of simulated years used to generate an expected cost estimate of each portfolio. While an infinite number of simulations for each portfolio would generate a perfectly smooth optimization surface (which could be optimized using some form of steepest descent approach), implicit filtering allows for efficient optimization of the problem by allowing the search to progress while reducing the number of simulated years required to generate expected cost values during each iteration.

Implicit filtering uses the finite difference gradient (as described by the difference between points on the finite difference stencil) to compute a search direction for descent. Unlike the classical steepest descent method, in which the negative gradient (or an approximation of the negative gradient) is used, implicit filtering uses a quasi-Newton model of the Hessian to scale the gradient, thereby accelerating convergence in the terminal phase of the iteration. The theory for implicit filtering [Kelley, 1999; Stoneking et al., 1992] and related algorithms [Audet and Dennis, 2003; Torczon, 1997; Kelley, 1999] explains how such methods overcome low-amplitude noise and also gives insight into the limitations of these methods. In particular, there is no guarantee that a global minimum will be found. While 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, which is the typical conclusion in convergence theorems for iterative methods for optimization. These results have also 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, implicit filtering for constrained optimization (IFFCO), 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] and Kelley [1999]). IFFCO handles constraints in two ways. Simple bound constraints on variables (e.g., \( N_C \geq 0 \)) 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

![Figure 1. Optimization landscape (constant values for \( \alpha_1/\beta_1 \) and \( \alpha_2/\beta_2 \)).](image-url)
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 CV AR which are generally reproducible to three significant figures. These parameters, as well as the $\alpha$ and $\beta$ 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 portfolio composition 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.

### 2.3. 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 two reservoirs have a combined storage capacity of approximately 5.8 million ac ft (MAF), with an additional 2.1 MAF of capacity set aside for flood protection (dead storage is roughly 30,000 ac ft). 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). Since the two reservoir came on line in 1968, combined U.S. storage in these structures has varied from a low of approximately 0.7 MAF to a high of 4.0 MAF. The hydrologic data record extends from 1970 to 2002, 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 U.S. share of reservoir inflows is allocated to the LRGV’s nearly 1600 water rights holders by the Rio Grande Watermaster’s Office, which also administers transfers between rights holders.

Ideally, the simulation described would be developed using long time series data sets that cover the same period for each hydrologic parameter (e.g., inflows, outflows), such that serial correlation in and between the data could be preserved. In cases where serial correlation is strong, expected supply and expected demand values would be estimated using conditional probability distributions based on current conditions (or those in the immediate past). In this case, however, the hydrologic data set is relatively limited (32 years) and use of only the sequential record would have reduced the analysis to a fairly narrow set of conditions. Attempts to expand consideration to a wider

---

**Table 1. Simulation Data Summary**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<td>Reservoir inflows ($i_i$), × 1000 ac ft</td>
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<td>88.5</td>
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<td>1919</td>
<td>1957</td>
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*Inflow, outflow, and loss data reflect the years 1970–2002 (see www.ibwc.state.gov).

*Spot lease prices reflect the years 1994–2003 (n = 1514) [Watermaster’s Office, 2004].
range of conditions by fitting existing hydrologic data to standard population models (e.g., lognormal, log-Pearson type III) using chi-square tests yielded very poor fits. The level of serial correlation in data sets and potential relationships between data sets were also explored to determine what other methods of hydrologic input could be used within the simulation.

[39] The Pearson test for serial independence was applied to the inflow time series, yielding evidence of weak autocorrelation in the monthly inflow data using both a 1- and 2-month lag ($R^2$ of 0.15 and 0.05, respectively). The relatively low level of serial dependence is likely a function of the longer time step (i.e., monthly), as well as the arid nature of the watershed and its lack of features that might enhance the system’s hydrologic “memory” (e.g., snowpack/snowmelt). Autocorrelation in monthly data is therefore unlikely to play a significant role in simulating regional supply conditions, particularly given that the Valley’s regional reservoir capacity is approximately 4 times average annual inflow. This capacity is sufficiently large that ignoring the weak autocorrelation in the data is unlikely to significantly affect simulated reservoir levels, and while interannual correlation of inflows could be an issue in multyear simulations, it is not a factor in the single annual cycles evaluated in this work. A similar evaluation of the 10-year record of monthly municipal usage (normalized by population) yielded a statistically significant, but weak serial correlation using a 1- and 2-month lag.

[40] With respect to relationships between variables, little evidence of correlation was observed between reservoir inflows and municipal water usage ($R^2 = 0.12$, as measured by the Spearman test for trend), a situation that is likely due to climatic differences between central Mexico, where the majority of inflows originate, and the Valley, which is hundreds of miles away on the Gulf Coast. Correlations were also weak between reservoir outflow and municipal usage ($R^2 = 0.18$), as outflow is dominated by irrigation releases, which in the Valley’s semiarid climate are largely dependent on a fixed schedule and tend to obscure the relatively small amount directed to municipal use. These analyses suggest that assuming independence in monthly values for inflow, outflow, and municipal usage could provide a reasonable basis for simulating regional conditions. As a result, values for these variables are randomly selected from the appropriate monthly data list within the simulation. Values for expected supply and expected demand are also computed directly from these monthly distributions (as opposed to conditional probability distributions predicated on current conditions).

[41] Allocations to regional rights holders (equation (7)) are calculated using an instream loss factor ($\xi_i$) of 0.175, and distributed pro rata across the region’s 1.9 million ac ft of water rights ($N_r_i$). As the number of regional rights substantially outstrips the annual average volume of available reservoir inflows, each acre foot of rights is allocated around 0.725 ac ft of water in an average year. December (initial) reservoir storage levels ($R_0$) are varied across historical December levels ranging from 0.8 to 2.2 MAF. The city’s share of this storage at the beginning of the year ($N_{r_i}$) is specified as a fraction of the total rights that the city holds ($f_{r_i}$), such that $N_{r_i} = f_{r_i} N_{r_i} R_{0}$. While it might seem logical to assume that high/low levels of $R_0$ and $f_{r_i}$ 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 $f_{r_i} (0.1, 0.3, 0.5)$ 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).

[42] 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 agricultural to urban water transfers. While economic incentives alone do not always translate to an increased volume of trades [DeMouche et al., 2003], this does appear to be the primary driver in the Valley [Chang and Griffin, 1992]. 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 [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]. The structure of the market leads to the assumption that spot market transaction costs are essentially negligible. While this assumption is reasonable within the Valley, it may not be so in many other regions, a factor which may bias this analysis in favor of spot market leases.

[43] 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 lease transactions between 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, 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 agricultural to urban transactions.

[44] An analysis was undertaken to explore statistical correlations between spot lease prices and several hydro-
logic 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 would incorporate consid-
eration 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 yield
very weak predictive relationships. Further analysis using
the Wilcoxon two-sample test strongly 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
(\(\hat{p}_L^B\)) or below (\(\hat{p}_L^B\)) this threshold (Table 1).

It should also be noted that while there is some
evidence of serial correlation (again using the Pearson test)
in the spot price data set as a whole, once the data
are separated into these two subsets the effects of serial
correlation becomes quite weak (1-month lag typically has
an \(R^2 < 0.10\)). In effect, it appears that when reservoir
storage drops below (rises above) the threshold level,
the mean monthly price increases (decreases), but subsequent
price variation about the mean is essentially random. This
randomness in spot market prices is likely due, in large part,
to the decentralized nature of the market. While the prices of
the most recent lease transactions can be obtained from the
watermaster’s office, it seems clear that most transactions
are completed with only a general knowledge of the current
level of water scarcity (i.e., reservoir level is low or its not).
This leads to a spread in prices, even those observed in the
same month with similar reservoir levels. Such behavior
might suggest that a high-volume buyer, motivated by large
potential savings, could find a lower price by increasing the
amount of time and effort spent looking for a seller.
However, correlations between spot market prices and the
volume purchased yielded no evidence of a statistically
significant relationship. Finally, consideration was also
given to adjusting the spot price data to reflect real prices
over the period 1993–2002. 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.

3. Results

All portfolios are developed with respect to a 1-year
planning horizon using the least favorable set of initial
conditions (\(R_0 = 0.1; R_0 = 0.8\) MAF), with minimum cost
portfolios 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. 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 \$0.1 million (Table 2). Reducing
reliability from 99 to 98% lowers annual costs by \$0.09
million, 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 $1.34 million, a reduction of a little over $0.25 million (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 25th to 75th percentile) extends from only $1.32 to $1.35 million. The CVAR is $1.37 million, small relative to the expected value, indicating that the use of options can significantly reduce expected costs while still limiting the city’s exposure to large cost fluctuations. The marginal cost of reliability ($0.1 million/percentage point from 99% to 99.5%) is approximately half of that for strategy A, but the marginal cost increases for both strategies 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 31 May 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 during the year; consequently, the values for $a_2$ (1.67) and $b_2$ (1.85) must be relatively high to ensure that the 99.5% reliability goal is met (Table 2). The value of $a_2$ declines

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<th>Strategy</th>
<th>Expected Cost, millions of dollars</th>
<th>CVAR, millions of dollars</th>
<th>$a_1$</th>
<th>$b_1$</th>
<th>$a_2$</th>
<th>$b_2$</th>
<th>Expected Year_End Supply, ac ft $\times$ 1000</th>
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</table>

*All portfolios assume an initial reservoir storage ($R_0$) of 0.8 MAF and an $f_{R_c} = 0.1$. 
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, \( \beta_2 \) rises from 1.85 to 2.15 as reliability declines, suggesting that when the city does exercise options, 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 \( \beta_2 \). Once \( \beta_2 \) 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 \( \beta_2 \) from 2.10 to 2.40 increases the volume of exercised options from 3888 to 3956 ac ft and raises expected costs less than a thousand dollars. By contrast, a similar variation in \( \alpha_2 \) 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 \( \beta_2 \) 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 \( \alpha \) and \( \beta \) 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 further sharpened at the cost of increased computation time.

[51] 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 several alternative portfolios are considered:

[52] In portfolio 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 exceeds expected costs by more than 10% (i.e., constraint (23) is employed).

[53] In portfolio 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.

[54] In portfolio C3, the city maintains no permanent rights and relies entirely on temporary transfers to meet demand and places no limits on cost variability.

[55] 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 before May, so \( \alpha_1 \) and \( \beta_1 \) are not applicable. In the latter portion of the year the \( \alpha_2 \) 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 (\( \beta_2 \) drops to 1.31, indicating that acquisitions are also smaller). Decreasing \( \alpha_2 \) and \( \beta_2 \) serves to lower reliability, with the marginal cost of reliability remaining relatively similar to that of strategy B from 99.5 to 99%.

[56] Expected cost drops significantly using strategy C2 ($0.92 million at 99.5% reliability). This is accompanied by a CVAR of $1.10 million, 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 left over at year’s end (7100 ac ft). Options again play no role, as the greater flexibility of the spot market and lack of concern over the CVAR make 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 unfavorable initial conditions result in the expected supply to expected demand ratio being quite low at the beginning of the year. Therefore, as long as \( \alpha_1 \) is set above this level, small variations in its value will have little impact on reliability (i.e., the city will always buy at the beginning of the year unless \( \alpha_1 \) were set very low). Small changes in acquisition size (\( \beta_1 \)), however, will 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.

[57] The expected cost of meeting 99.5% reliability through strategy C3 declines to $0.58 million with a portfolio that relies entirely on spot market leases. Dependence on spot leases results in a CVAR that is roughly twice the expected cost, although still lower than the expected cost of the A, B, and C1 strategies. The city begins the year with no permanent rights and will need to buy water immediately, so \( \alpha_1 \) values are meaningless. The high \( \beta_1 \) (2.56) points to a large acquisition in \( t = 0 \), large enough that only subtle adjustments to supply are required over the remainder of the year to meet reliability objectives in most years. In this case, the size of the initial acquisition and the fact that it is always the same size (for a given set of initial conditions) mean 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.

[58] When considering the practicality of each strategy, the realities associated with managing a utility make it unlikely that strategy C3 would be widely adopted. Furthermore, the increase in CVAR that occurs when switching from C1 to C2 ($0.31 million at 99.5% reliability), 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. Table 3 describes minimum cost portfolios (99.5% reliable) developed using strategies B and C2 under more favorable initial conditions. Portfolios are most sensitive to changes in the initial water supply \( f_{\text{R}_0} \), with the expected cost of strategy B \( (R_0 = 1.5 \text{ MAF}) \) declining from $1.32 to $0.66 million as \( f_{\text{R}_0} \) rises from 0.1 to 0.5, respectively. The portfolio developed using strategy C2 maintains greater flexibility through the use of spot leases, so while costs decline with rising \( f_{\text{R}_0} \), the change is relatively small (of the order of $0.01 million). Changes in initial reservoir storage \( (R_0) \) affect only the price of options and leases (not the amount that must be bought), and while higher initial storage levels result in slightly lower expected costs, there is little impact on portfolio composition. The expected costs of a portfolio using strategy B \( (f_{\text{R}_0} = 0.1 \text{ or } 0.3) \) decline approximately $0.1 million as \( R_0 \) rises from 1.5 to 2.2 MAF and the effects on a portfolio developed using strategy C2 are even smaller.

Both strategies B and C2, regardless of initial conditions, are expected to leave the city with at least 30% of its average annual water supply (21,000 ac ft) available for use in the next year. The same applies for any of the strategies described in Table 2, with the exception of C3 (all water obtained via spot market), implying that even though this analysis is limited to a 1-year horizon, the approach is not likely to generate portfolios that will leave the city in an untenable position at year’s end (i.e., without any water). The approach described in this paper may therefore provide a reasonable starting point for future work seeking to develop long-term portfolios.

Varying the relative distribution of leases and options provides a means of “fine tuning” the trade-offs 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 4 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 ($0.05 million) than one without options, but with a somewhat lower CVAR ($1.12 versus $1.095 million).

While the reduction in CVAR is modest, it should be noted that there are additional benefits that might be associated with some form of long-term option that are not included in this analysis. When either transaction costs or transaction risk are relevant factors, long-term option contracts are likely to become increasingly attractive relative to spot market leases, but quantifying these values is difficult. As
part of a 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 an assessment of multiyear strategies is beyond the scope of this work, it does appear that some variation of C2 might serve as a foundation for a city seeking to lower long-term water supply costs through the use of multiyear option contracts. Annual increases in the number of 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.

4. Conclusions

Many 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. 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 significantly. While options play a relatively limited role in the portfolios developed in this analysis, some of this is attributable to assumptions regarding the spot market (i.e., no transaction costs, unlimited availability) and a risk-neutral utility. A more risk-averse utility facing a less “liquid” spot market might find options more attractive, particularly when developing multiyear water supply strategies. In addition, while these results suggest that increased use of temporary transfers can lower costs in a single year context, the degree of savings such strategies might produce over the long term is still an open question.

With respect to the solution technique, implicit filtering proves to be an effective search method for the noisy optimization (i.e., expected cost) surface generated in this type of water resource problem. The IFFCO algorithm provided repeatable solutions for minimum expected cost and reliability that were accurate to three significant figures. It appears likely that this method may have broader applications within the field of water resource management.

While these results are limited to a 1-year horizon, they suggest that substantial cost savings are possible through a more diversified approach to water supply management. As such, these results may provide useful information to cities seeking to develop more cost effective supply strategies in the face of growing demand and increasing resource development costs. 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 improving capabilities in these areas as well.

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References

Hull, J. C. (1999), Options, Futures, and Other Derivatives, Prentice-Hall, Upper Saddle River, N. J.
South Central Texas Regional Water Planning Group (2000), Water supply options for south central Texas, Tex. Water Dev. Board, Austin.
Young, R. A. (1986), Why are there so few transactions among water users?, Am. J. Agric. Econ., 68(6), 1143–1151.

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