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ORIGINAL ARTICLE

Option contracting in the California water market

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Abstract Temporary water transfers, as achievable under option contracts, capture gains from trade that would go unrealized if only permanent transfers of water rights were possible. This paper develops a bilateral option contracting model for water which includes the possibility of conveyance losses and random delivery. Seller-optimal and socially optimal option contracts are characterized in terms of relevant base and strike prices, as well as contract volumes, from an ex-ante and an ex-post point of view. Lastly, welfare gains are estimated, and actual contract prices in California are compared to model-predicted prices.

Keywords Bilateral contracting · Capacity-reservation contracts · Option pricing · Real options · Water resources

JEL Classification D02 · D21 · D42 · D61 · D71 · L14 · L95 · Q25

1 Introduction

In an economic environment with complete information and zero transaction cost, the seminal theorem by Coase (1960) predicts that as long as property rights are well-defined, gains from trade will be realized, leading to Pareto-efficient outcomes. In practice, the presence of transaction cost and institutional resistance may contrive

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to make trade unprofitable, infeasible, or both. To the extent transaction cost and institutional resistance depend on the *terms* of the exchange agreement between two parties, the efficiency of outcomes can be influenced by the choice of the contract structure.

The exchange of permanent rights to natural resources such as water is often characterized by high transaction cost and significant institutional resistance. The transaction cost comprises legal fees and administrative overhead during the contracting phase, as well as the cost associated with the search and concomitant delays in the antecedent matching phase. Even after a contract has been agreed upon by the trading parties, it typically requires approval by a governing body, resulting in additional legal expense, environmental or community mitigation fees, and other overhead. Institutional resistance to a permanent rights transfer stems in part from the complex nature of due diligence mandated by legislation (which often involves an environmental review and third-party consultation) as well as the corresponding interaction of the different stakeholders.[1]

Temporary resource transfers, or leasing agreements, can reduce the institutional resistance and lower the transaction cost that impede permanent transfers. In so doing, they facilitate gains from trade that would otherwise go unrealized. Temporary resource transfers ensure the retention of the underlying resource right and therefore do not require long-term commitments by affected stakeholders. Since they typically impose only a small downside risk to the environment, they often enjoy an accelerated review process. The relatively small environmental risk can also play an important role in facilitating community approval. Finally, the valuation of a one-time transfer is inherently less complex than that of a perpetuity, not least of all due to the reduction in uncertainty surrounding the value in use and the resource availability at future dates. This reduces the cost in both the matching and the contracting phase. Standard agreements can be drafted, so that resource transfers more and more resemble market rather than nonmarket transactions. Moreover, repeated short-term agreements represent a natural implementation of relational long-term contracting (see, e.g., Levin 2003), where at each renewal time new information about contingencies (such as uncertainties about the trading parties' outside options) can be incorporated. There are examples of successful temporary resource transfers in fishing (Newell et al. 2005), grazing (Rimbey et al. 2007), and more recently also in water markets (cf. Section 3).

In this paper, a model for bilateral water option contracts with uncertain exercise fulfillment and outside options is constructed. The structure of seller-optimal contracts is compared to that of socially optimal contracts. The impact of changes in model parameters on the contract design is also examined. The model is calibrated to transfers for a large water district in the California water market whose recent option contracts are shown to have parameters that lie in between the seller-optimal and socially optimal choices.

[1] Peluso (1992), McKean (2002), and Agrawal (2002) report community resistance to the nationalization of forest lands in Java and India. Pinkerton (1999) gives an account of resistance to the allocation of fishing licenses by the local community of West Coast Vancouver Island. Thompson (1993) and Hanak (2003, 2005) describe resistance to the sale of water rights by local communities in the Western United States. Kahn (2000) reports the story of Fijian resistance to the sale of land to American and British companies for timbering of mahogany. In 2000, a state coup was attempted to gain control of the rights to timber extraction.

1.1 Background on the California water market

Permanent water transfers in the California water market are associated with both high transaction cost and considerable institutional resistance (Hanak 2003, 2005; Hanak and Howitt 2005; Zilberman and Schoengold 2005). Members of farming communities whose livelihoods depend on crop cultivation (e.g., equipment sales- and repairmen, marketers, and millers), and those who do not stand to gain financially from the sale of water, may seek political means to block water transfers (Thompson 1993). In agricultural water districts where all members have voting rights, as opposed to just landowners, there may be sufficient political power to block transfers. Even in districts with landowner voting rights, there is an incentive for farmers who plan to purchase extra water to block intradistrict transfers, thereby keeping the interdistrict prices low. The due diligence requirements, which include an assessment of third-party and community impacts and a full environmental review under the California Environmental Quality Act (CEQA), contribute to the high transaction cost.

The expense of drafting a long-term transfer agreement is often significant. For example, the largest urban-agricultural transfers in California to date have been those negotiated among Imperial Irrigation District (IID), San Diego County Water Authority (SDCWA), Metropolitan Water District of Southern California (MWD), and Coachella Valley Water District (CVWD), as part of the Quantification Settlement Agreement (QSA) on the Colorado River (Torres 2003). IID is a large irrigation district in Southern California with first-priority rights to Colorado River water. Under the QSA, completed in 2003, IID agrees to transfer up to 200,000 acre-feet (af) of water to SDCWA and up to 103,000 af to MWD and CVWD in a given year, for 75 years. In addition, SDCWA agreed to provide a community mitigation fund to offset the socio-economic impacts of the water transfer, with an initial upfront payment of $10 million. The time required to negotiate a large permanent water-rights transfer (for the QSA more than five years, from 1997 to 2003) renders it difficult as a tool for short-term supply-risk management. Another transaction cost associated with long-term contracts is the formalization and management of the renegotiation process as environmental and socio-economic boundary conditions evolve.

In lieu of permanent or long-term transfers, temporary water transfers can avert costly supply shortfalls. Recognizing the importance of temporary transfers in managing short-term supply risk, the Department of Water Resources (DWR) instituted the Emergency Drought Water Bank (EDWB) during a critically dry period in the early 1990s. In the EDWB's first year of operation, 1991, DWR purchased over 400,000 af of water from agricultural districts for $125/af and then sold the water to urban agencies for $175/af, with the price mark-up intended to cover the transaction cost.[2] The EDWB (later renamed to Dry Year Water Purchase Program) was operated again in 1992 and 1994, and then, more recently, in 2001, 2002, and 2003. This centralized operation has the advantage of buyer aggregation, as well as of reliable access to the DWR-controlled infrastructure. In the long-term, however, it is doubtful that EDWB operations can scale to adequately and efficiently meet the needs of the hundreds of

[2] Just slightly over half of the water purchased was actually sold that year; a portion was stored until the following year and sold then.

individual water districts in California that could reasonably incorporate temporary transfers into their water-management strategies.

Option contracts provide an alternative means for managing water supply risk by implementing temporary transfers. In an option contract the buyer–seller interaction takes place in two periods. In the first period, the seller announces a *base price* (or, capacity-reservation price) p and a *strike price* s for each unit of the good, as well as a nonnegative upper bound K for the size of the contract. The buyer subsequently chooses a contract size $Q \in [0, K]$. At this time both the buyer's downstream demand and the spot market price (representing the value of the seller's outside option) are uncertain. In the second period, the uncertainty about the buyer's downstream demand resolves, and the buyer announces the quantity $z \in [0, Q]$ of options to exercise. The seller releases the quantity z into the conveyance system, and the buyer obtains $y = \lambda z$ with probability $\phi \in (0, 1]$, where $\lambda \in (0, 1]$ represents the conveyance-loss coefficient and $1 - \phi$ is the probability of a complete infrastructure failure, e.g., as a result of low priority in a critical conveyance system whose capacity is subject to random fluctuations, such as the Bay Delta in California. An infrastructure failure (or non-conveyance) is typically realized after the option contract is signed but before the buyer's option exercise decision is made. Depending on her production lead time, the seller uses either the quantity $K - z$ or $K - Q$ to produce an equal quantity of consumption goods that are sold on a spot market at the price m.

In 2003, the Metropolitan Water District of Southern California (MWD), the largest water intermediary in the state, initiated option contracts, and they have been repeatedly used since.[3] The contracts represent a shift from the focus on permanent or long-term water transfers from agricultural to urban water districts. There have been 15 short-term option contracts signed between 2003 and 2008. In contrast to long-term contracts, which may take several years to negotiate and millions of dollars in environmental and community mitigation fees, these option contracts were agreed upon and executed in the course of several months with limited administrative overhead.

1.2 Related literature

The bilateral option pricing model developed in this paper is based on earlier work by Wu et al. (2002), Spinler (2003), and Spinler and Huchzermeir (2006) on the pricing of capacity options for nonstorable goods such as electricity. Wu et al. (2002) propose a two-part tariff for a risk-neutral buyer whose payoff depends on the state of the world only through an uncertain spot market price. Spinler and Huchzermeir (2006), based in part on Spinler (2003), consider the additional effects of demand and cost uncertainty

[3] In 2003, MWD signed contracts (for a total volume of 146,230 af) with Glenn–Colusa Irrigation District, Western Canal Water District, Richvale Irrigation District, Reclamation District 108, River Garden Farms, Natomas Central Mutual Water Company, Meridian Farms Mutual Water Company, Pelger Mutual Water Company, Pleasant Grove-Verona Mutual Water Company, Sutter Mutual Water Company, and Placer County Water Agency. Only the options from the contract with the Placer County Water Agency were ultimately not called. Agency concerns with respect to the farmers who, under district-negotiations, are forced to sell their water and then resist are probably not of great consequence. As currently arranged, the farmers have the chance to voluntarily subscribe to the leasing agreement and to date the contracting districts have reported a surplus of voluntary subscriptions.

as well as the interaction of seller-optimal option contracts with a parallel spot market for capacity. The latter interaction between supply-chain contracting and spot-market procurement with simple separable payoff functions is explored by Mendelson and Tunca (2007), where all market participants can also have private information. In all of these linear pricing models (with linear pricing equilibria), the seller retains all of the bargaining power, and the buyer's utility is separable in the different contracting components as well as uncertainty. Such separability is not appropriate in the water market, where the buyer's shortage and overage costs depend nonlinearly on the amount of water procured and the realized demand. As a consequence, the option pricing rules in our model are generally different from the ones proposed in earlier papers on capacity-reservation contracts. Yet they are consistent with the standard theory of multiproduct pricing of complementary goods by a monopolist (Baumol and Bradford 1970; Crew and Kleindorfer 1986). An additional specific feature in water option contracting is the possibility of transmission losses and infrastructure failures, which may ex-post jeopardize the execution of an option contract and therefore influence its ex-ante valuation.

In the case of the electricity market, the seller is interested in offloading excess generation capacity rather than selling the underlying asset (the generation facility). The buyer is interested in short-term access to additional generation capacity. Outright purchase of the generation facility by the buyer may be neither financially viable nor desirable. The analogy to contracting in the water market is direct: the seller is interested in offloading water in a given period but disinterested in selling her underlying water right. The buyer contracts to meet a short-term supply shortage. A slight difference in the contracting problem is with regard to the buyer's and the seller's outside option. The treatment of capacity options in the electricity market, with potential applications to the chemical and plastics industries, has assumed the presence of a spot market. There is as of yet no spot market for water.[4] Hence, the water option pricing model considered here treats contracting in its absence.

The distinction between the pricing of a capacity option and a financial option, e.g., a stock option, lies in the nature of the underlying asset. The no-arbitrage pricing model for a stock option, as developed by Black and Scholes (1973), requires, in addition to perfect competition on the market, two separate price processes—that of the stock and that of the option.[5] In the case of a capacity option, a stand-alone valuation can be obtained using a real-options framework (cf. Dixit and Pindyck 1994; Paddock et al. 1988; Trigeorgis 1996), without the need for a market, or, equivalently, a price process for the underlying capital-intensive asset. Kleindorfer and Wu (2003) describe the trading of capacity options on business-to-business exchanges in the presence of an active spot market. In the context of water markets there is no price process defining the value of a share of a water right. In the context of agricultural futures and

[4] Such spot markets are beginning to develop worldwide, e.g., under the National Water Initiative in Australia (ACCC 2008).

[5] A 'real options' framework (cf. Dixit and Pindyck 1994; Paddock et al. 1988; Trigeorgis 1996) can be used to describe the (sequential, irreversible) investment in risky projects, which require an initial capital outlay, corresponding to an option fee (or, e.g., 'capacity-reservation price'), and possibly additional sequential outlays to continue the project in the future, corresponding to one or multiple strike prices.

options on futures, Aase (2004) applies the Black–Scholes results to the pricing of an option on a crop future. This is achieved through construction of a second price process based on the prices of yield insurance on the Chicago Board of Trade. The Aase model implies that *if* a separate insurance market for fluctuations in annual water deliveries were developed, then the standard financial pricing model could be usefully applied to water options.[6]

1.3 Outline

The rest of the paper is organized as follows. Section 2 introduces the bilateral option contracting model. Section 2.1 characterizes seller-optimal contracts, and Section 2.2 discusses efficiency properties of the contract, comparing the seller-optimal contract to the ex-post and ex-ante welfare-optimal contracts. Section 2.3 treats surplus extraction by the seller. Section 2.4 investigates the sensitivity of the optimal contract to parameter shifts in the buyer's and seller's value functions. The possibility of an outside option available to the buyer at a fixed price arises here. Finally, Section 2.5 considers standard linear and quadratic model specifications as simple examples. The application of the contracting model to the California water market is the subject of Section 3. Section 3.1 introduces the model specification. In Section 3.2, the social welfare gains under contracting are estimated. In Section 3.3, option-price trends in the California market are discussed. The welfare gains under contracting are sensitive to the assumptions regarding both the expected commodity price and the marginal cost of electricity used in the north–south conveyance of water. Section 4 offers conclusions and directions for future research.

2 Model

A buyer ("he") and a seller ("she") enter into an option contract for a divisible good such as water. The buyer is an intermediary who needs to cover an uncertain future downstream demand for the good or derivatives thereof. The seller enters into the contract as an alternative to using the good as an input to her own production of consumables (e.g., crops), which are sold on a spot market at a future date. In the context of water, the setting is as follows: the seller, a farmer, has access to a market for the crop that she cultivates, with water as a production input. The buyer, an urban water intermediary, has no access to a spot market for water. There are two cases of interest. In the first, the buyer has no outside supply option. In the second, the buyer possesses an outside supply option at a fixed unit price. Analogous to capacity options for electricity, water delivery options are an alternative to a direct purchase of the production technology (here the water right).

Our bilateral option contracting model allows for uncertainty with regard to both the buyer's and the seller's reservation values, where the former's is a function of

[6] Another approach to the pricing of water options is Luenberger (2001, 2002) zero-level pricing method, based on the Capital Asset Pricing Model, that relies on a geometric projection of the prices of similar traded assets.

uncertain demand for water and the associated shortage cost of water, and the latter's is a function of the spot market price for the consumption good, e.g., the crop. In accordance with the realities in the California water market, the analysis assumes symmetry of information; the seller, who moves first by announcing the terms of the option contract, possesses a description of the buyer's value function. The model captures the possibility of infrastructure failure (or non-conveyance), the reality of system losses suffered during conveyance, and the presence of a conveyance (or delivery) cost.

2.1 Seller-optimal contracting

As in Wu et al. (2002) the buyer and seller play a Stackelberg leader-follower game, where the seller first announces a *base price* p and a *strike price* s for each unit of the good, as well as a nonnegative upper bound K for the size of the contract. However, unlike in Wu et al., where buyer and seller face the same source of uncertainty in the form of the future spot market price, in this situation the buyer and seller have to deal with different sources of uncertainty. The buyer's uncertain downstream demand $\tilde{D}$ follows a cumulative distribution function (cdf) F on $\mathbb{R}_+$ with finite mean and variance. The uncertain spot market price $\tilde{m}$ has the cdf G on $\mathbb{R}_+$ with finite mean $\bar{m}$. Note that $\tilde{D}$ and $\tilde{m}$ may be jointly distributed (i.e., correlated), in which case F and G are to be interpreted as the relevant marginal cdf's. In the second period, the buyer announces the quantity $z \in [0, Q]$ of options to exercise, which the seller releases into the conveyance system provided that (with probability $1 - \phi \in (0, 1]$) there is no infrastructure failure. For simplicity, we assume that the infrastructure failure and the random vector $(\tilde{D}, \tilde{m})$ are statistically independent. Upon the release of z into the system the buyer obtains the quantity $y = \lambda z$, where $\lambda \in (0, 1]$ represents the conveyance-loss coefficient.[7] An infrastructure failure is realized after the option contract is signed but before the buyer's option exercise decision.

In the second period, the buyer's downstream demand D realizes. Given the exercise price s and the available quantity of options Q, the buyer solves the problem

$$V(Q, D, s) = \max_{z \in [0, Q]} \{v(\lambda z, D) - sz\}, \tag{1}$$

where $v(y, D)$ is the buyer's (smooth) second-period gross payoff, given an amount y of the good and a downstream demand of D. It is assumed that the buyer's second-period payoff function $v(y, D)$ is concave in y, locally nonsatiated in y (such that $v_y > 0$) and has nondecreasing differences in (y, D), so that

$$v_{yy} \le 0 \le v_{yD}. \tag{2}$$

[7] More generally, it is possible to model λ as the realization of a random variable $\tilde{\lambda}$ describing the state of the infrastructure. Since this leads to a more complex formalism with very similar results, we have opted for this simpler variant to capture the notion of random fulfillment. For example, the San Diego County Water Authority currently assesses a 50% probability of non-fulfillment of its contracts due to restrictions on water exports through the San Francisco Bay Delta.

Concavity corresponds to the notion of nonincreasing marginal utility, while nondecreasing differences (or supermodularity) means that the marginal utility (e.g., determined by the set downstream price) weakly increases as downstream demand for the good increases. The concavity and supermodularity assumptions are satisfied for all of the model specifications below (cf. Section 2.5). Note that in general, the buyer's payoff is not monotonic in the second argument because there can be an overage cost of having too much of the good and an underage cost when not enough is available. An optimal solution to (1) is given by

$$z(Q, D, s) = \sup\{q \in [0, Q] : \lambda v_y(\lambda q, D) \geq s\}, \tag{3}$$

where we set $\sup \emptyset = 0$. The optimal second-period exercise $z(Q, D, s)$ corresponds to the largest quantity such that the buyer's expected marginal utility for the good exceeds the strike price. The buyer's expected first-period payoff when choosing an available contract of size Q is therefore

$$\bar{V}(Q, s) = \phi E\left[V(Q, \tilde{D}, s) \middle| Q, s \right] + (1 - \phi)\bar{V}_0, \tag{4}$$

where $\bar{V}_0 = E\left[v(0, \tilde{D})\right]$ is the buyer's (expected) reservation value. Note that since the maximized objective function in (1) is nondecreasing in Q, the expected first-period utility $\bar{V}$ must also be nondecreasing in Q. Given the contract-parameter tuple (p, s, K), the buyer's first-period problem is to maximize his expected net payoff,

$$\max_{Q \in [0, K]} \{\bar{V}(Q, s) - pQ\}. \tag{5}$$

Using the envelope theorem on the buyer's maximized second-period objective function V in (1) it is

$$\frac{\partial \bar{V}(Q, s)}{\partial Q} = \phi E\left[\frac{\partial V(Q, \tilde{D}, s)}{\partial Q} \middle| Q, s \right] = \phi E\left[\kappa(Q, \tilde{D}, s) \middle| Q, s \right] \equiv \phi \bar{\kappa}(Q, s), \tag{6}$$

where $\kappa(Q, D, s) = [\lambda v_y(\lambda Q, D) - s]_+$ is the Lagrange-multiplier in problem (1),[8] associated with the constraint $z \leq Q$. Since by assumption $v_{yD} \geq 0$, the optimal solution $z(Q, D, s)$ must be nondecreasing in D, so that (setting $\inf \emptyset = \infty$ and $\sup \emptyset = 0$)

$$\bar{D}(Q, s) = \inf\{D \geq 0 : \lambda v_y(\lambda Q, D) \geq s\}, \tag{7}$$

$$\underline{D}(s) = \sup\left\{D \geq 0 : \lambda v_y(0, D) \leq s\right\} \tag{8}$$

[8] For any $x \in \mathbb{R}$, we define $[x]_+ = \max\{0, x\}$.

are demand thresholds beyond which the buyer would exercise either all available options or no options at all, i.e.,

$$D \geq \bar{D}(Q, s) \Rightarrow z(Q, D, s) = Q,$$
$$D \leq \underline{D}(s) \Rightarrow z(Q(p, s, K), D, s) = 0.$$

Hence,

$$\bar{\kappa}(Q, s) = \int_{\bar{D}(Q,s)}^{\infty} \kappa(Q, D, s) dF(D) = \int_{\bar{D}(Q,s)}^{\infty} \big(\lambda v_y(\lambda Q, D) - s\big) dF(D) \geq 0, \tag{9}$$

and, using the Leibniz rule as well as Eq. 7,

$$\frac{\partial \bar{\kappa}(Q, s)}{\partial Q} = \lambda^2 \int_{\bar{D}(Q,s)}^{\infty} v_{yy}(\lambda Q, D) dF(D). \tag{10}$$

The buyer's maximized objective function in (1) is therefore concave in Q, and the optimal solution to the buyer's first-period problem (5) is

$$Q(p, s, K) = \sup\{q \in [0, K] : \phi\bar{\kappa}(q, s) \geq p\}. \tag{11}$$

It is best for the buyer to purchase the largest quantity of options, up to a maximum of K, such that his first-period expected net payoff is nonnegative at the margin.

Lemma 1 *The buyer's demand $Q(p, s, K)$ for options in Eq. 11 is nonincreasing in $(p, s, -K)$. Moreover, if v is strictly concave in y, then, as long as $0 < Q(p, s, K) < K$,*

$$Q_p = 1/(\phi\bar{\kappa}_Q) < 0 \quad \textit{and} \quad Q_s = -\bar{\kappa}_s/\bar{\kappa}_Q < 0, \tag{12}$$

where $\bar{\kappa}_Q = \lambda^2 \int_{\bar{D}}^{\infty} v_{yy}(\lambda Q, D) dF(D) < 0$ and $\bar{\kappa}_s = -(1 - F(\bar{D}))$.

Proof All proofs are provided in the Appendix.

From Lemma 1 an option contract can be viewed as a standard non-Giffen good, for which the buyer's demand is decreasing in the base price p and strike price s. Similarly, as the following lemma shows, the buyer's expected exercise quantity in the second period,

$$\bar{z}(p, s, K) = \phi E\left[z(Q(p, s, K), \tilde{D}, s) \middle| p, s, K \right], \tag{13}$$

can also be viewed as a non-Giffen demand for option exercise.

Lemma 2 *The expected number of options* $\bar{z}(p, s, K)$ *exercised by the buyer in Eq. 13 is nonincreasing in* $(p, s, -K)$*. Moreover, as long as* $0 < \bar{z}(p, s, K) < K$*, it is*

$$\bar{z}_p = \phi(1 - F(\bar{D}))\, Q_p < 0 \;\; \textit{and} \;\; \bar{z}_s = \frac{\phi(1 - F(\bar{D}))}{1 - \delta}\, Q_s < 0, \tag{14}$$

where $\delta = (1/\bar{z}_s) \int_{\underline{D}}^{\bar{D}} z_s(Q, D, s)\, dF(D) \in (0, 1)$.

Based on the last two lemmas, it is natural to view the seller's option pricing problem as a classical multi-product pricing problem. The seller's revenue comes from the initial sale and subsequent exercise of the options, while her cost is composed of an expense for the transport (conveyance) of the good to the buyer and of an opportunity cost from not being able to use the good herself, either *ex ante* or *ex post* relative to the option exercise date. The *seller-optimal pricing problem* is therefore

$$\begin{aligned} &\max_{p,s} \{pQ(p, s, K) + s\bar{z}(p, s, K) - C(Q(p, s, K), \bar{z}(p, s, K))\}, \\ &\text{s.t.} \quad 0 \le Q(p, s, K) \le K, \end{aligned} \tag{15}$$

where the seller's expected total cost is

$$C(Q, \bar{z}) = E[c(Q, z(Q, \tilde{D}, s), \tilde{D}, \tilde{m}) | p, s, K] = A(Q) + B(Q)\bar{z}, \tag{16}$$

with $A(Q)$ and $B(Q)$ nondecreasing, differentiable, convex functions. For this we assume that the seller's cost function $c(Q, z, D, m)$ is quasi-linear in z, so that

$$c(Q, z, D, m) = a(Q, D, m) + b(Q, D, m)z \tag{17}$$

for all admissible $(Q, D, m) \ge 0$, where $a(\cdot, D, m)$, $b(\cdot, D, m)$ are nondecreasing, differentiable, convex functions, and $b \ge 0$. This implies that the marginal expected cost with respect to both Q and $\bar{z}$ is nonnegative, i.e., $C_Q, C_{\bar{z}} \ge 0$.

Remark 1 The following two forms of the seller's total cost are common. First, if the seller must forgo productive use of the good under contract in the first period, then only $K - Q$ units of the finished good are available for sale on her market, at the random price $\tilde{m}$, so that in expectation $C(Q, \bar{z}) = -(\bar{m} - \bar{c})(K - Q) + w\bar{z}$, i.e.,

$$A(Q) \equiv -(\bar{m} - \bar{c})(K - Q) \quad \text{and} \quad B(Q) \equiv w, \tag{18}$$

where $\bar{c}$ corresponds to a (constant) marginal production cost, w is the cost of conveyance (or delivery), and $\bar{m}$ is the seller's expected market price for his own finished goods. Second, if the seller—e.g., because her production lead times are relatively short—can employ all goods for which options are not exercised in the second period, then $C(Q, \bar{z}) = -(\bar{m} - \bar{c})(K - \bar{z}) + w\bar{z}$, i.e.,

$$A(Q) \equiv -(\bar{m} - \bar{c})K \quad \text{and} \quad B(Q) \equiv \bar{m} + w - \bar{c} \tag{19}$$

with the same constants as before. Of course, the seller's expected cost could in principle be of a different form. For example, it may be possible that $c(Q, z, D, m)$ depends nonlinearly on z, so that the expected cost is no longer quasi-linear in $\bar{z}$. In that case, the following analysis remains applicable but the results are more complex, since it is not possible to restrict attention to the expected option exercise quantity when analyzing the seller's optimal option pricing decision. In the practice of the California water market, the seller's total cost is well approximated by an expected-cost function that is quasi-linear in $\bar{z}$.

Proposition 1 (Seller-optimal contract) *(i) At an interior solution, where $0 < Q(p, s, K) < K$, the seller-optimal option contract (p, s, K) is such that*

$$p = \left(\frac{(1-\delta\varepsilon_s)\varepsilon_p}{\varepsilon_p + \varepsilon_s - (1+\delta\varepsilon_p\varepsilon_s)}\right)\left(C_Q + \frac{\phi(1-F(\bar{D}))}{1-\delta\varepsilon_s}C_{\bar{z}}\right) \geq 0,$$
$$s = \left(\frac{(1-\delta\varepsilon_p)\varepsilon_s}{\varepsilon_p + \varepsilon_s - (1+\delta\varepsilon_p\varepsilon_s)}\right)\left(\frac{1-\delta}{1-\delta\varepsilon_p}\frac{C_Q}{\phi(1-F(\bar{D}))} + C_{\bar{z}}\right) \geq C_{\bar{z}},$$

and K is all of the seller's available capacity, where $\varepsilon_p = -pQ_p/Q$ and $\varepsilon_s = -s\bar{z}_s/\bar{z}$ are the own-price elasticities of the buyer's demand for option contracts and for his expected option exercise, respectively. (ii) The solution for $Q(p, s, K) = q \in \{0, K\}$ is determined by

$$p = \phi\bar{\kappa} \geq 0,$$
$$s = \left(\frac{\delta\varepsilon_s}{1-\delta\varepsilon_s}\right)\left(\frac{1-\delta}{\delta\varepsilon_p}\frac{\bar{\kappa}}{1-F(\bar{D})} - C_{\bar{z}}\right) \geq C_{\bar{z}},$$

with the same notation as in part (i), and $\bar{\kappa} = \bar{\kappa}(q, s)$ is obtained from Eq. 9.

Proposition 1 defines the optimal contract prices in terms of the own-price elasticities of the options Q and the expected option-exercise quantity $\bar{z}$. A seller facing a nonnegative marginal cost for sold and exercised options (with $C_Q, C_{\bar{z}} \geq 0$) never subsidizes the purchase or exercise of such options. In particular, the strike price s is never strictly less than the seller's marginal cost $C_{\bar{z}}$ of fulfillment. The proof (cf. Appendix) shows that as long as there is a difference between the expected option-exercise quantity, $\bar{z}$, and the expected full contract delivery, $\phi\left(1 - F(\bar{D})\right)Q$, e.g., because of intermediate demand realizations, the strike price exceeds $C_{\bar{z}}$. This extends the logic of Wu et al. (2002), who (under the implicit assumption that $v_{yD} = 0$) establish equality between s and $C_{\bar{z}}$, to the case where the buyer's payoff v is not additively separable in D and y. The complementarity between Q and $\bar{z}$ from the buyer's point of view implies that, while p is always nonnegative, it is possible that $p < C_Q$, i.e., the marginal opportunity cost of reserving capacity may exceed the capacity-reservation price.

Using a number of simple algebraic manipulations (which are omitted), the seller-optimal contract in Proposition 1 can be formulated in terms of two standard markup rules for a multiproduct monopolist with complementary goods (Baumol and Bradford 1970; Crew and Kleindorfer 1986).

Corollary 1 (Seller-optimal markup rule) *(i) At an interior solution, i.e., when* $0 < Q(p, s, K) < K$*, the relative markups of the seller-optimal contract* (p, s, K) *satisfy*

$$\frac{p - C_Q}{p} = \frac{1}{\varepsilon_p} - \frac{\varepsilon_p}{\bar{\varepsilon}_p} \frac{s\bar{z}}{pQ} \left(\frac{s - C_{\bar{z}}}{s} \right) \leq \frac{1}{\varepsilon_p},$$

and

$$\frac{s - C_{\bar{z}}}{s} = \frac{1}{\varepsilon_s} - \frac{\bar{\varepsilon}_s}{\varepsilon_s} \frac{pQ}{s\bar{z}} \left(\frac{p - C_Q}{p} \right) \gtreqless \frac{1}{\varepsilon_s},$$

where $\bar{\varepsilon}_p = -p\bar{z}_p/\bar{z}$ *and* $\bar{\varepsilon}_s = -sQ_s/Q$ *are positive cross-price elasticities. (ii) When* $Q(p, s, K) = 0$ *(resp.* $Q(p, s, K) = K$*), each equality is replaced by an inequality,* $\leq$ *(resp.* $\geq$*).*

Remark 2 In the case where the buyer's downstream demand is perfectly known, i.e., when $\tilde{D} = D_0$ for some $D_0 \geq 0$, a monopoly pricing rule holds with respect to the *all-inclusive tariff* $r \equiv p + \phi s$. The resulting contract is a simple forward agreement under which the product is delivered with the positive probability ϕ. By considering the buyer's second-period problem (1) we obtain the shadow value $\kappa = \bar{\kappa} = \left[\lambda v_y(\lambda Q, D_0) - s\right]_+$ for the constraint $z \leq Q$, and (for $z = z(Q, D_0, s) > 0$) the optimality condition $\lambda v_y(\lambda z, D_0) = s + \kappa$. Similarly, the buyer's first-period problem (5) yields (for $Q = Q(p, s, K) \in (0, K)$) that $\lambda v_y(\lambda Q, D_0) = s + (p/\phi)$. Since in the absence of demand uncertainty it is $z = Q$, we obtain the seller's profit-maximization problem in the form[9]

$$\max_r \{rQ - C(Q, \phi Q)\}, \quad \text{subject to } \phi\lambda v_y(\lambda Q, D_0) = r.$$

The resulting monopoly pricing rule becomes

$$\frac{r - \mathrm{MC}(Q)}{r} = -Q \frac{\partial \ln v_y(\lambda Q, D_0)}{\partial Q} \quad \left(= -\lambda Q \frac{v_{yy}(\lambda Q, D_0)}{v_y(\lambda Q, D_0)} \right),$$

where $\mathrm{MC}(Q) = C_Q(Q, \phi Q) + \phi C_{\bar{z}}(Q, \phi Q)$ is the seller's marginal cost of providing the quantity Q of the good which will be called in the future with probability ϕ. □

When does a nontrivial seller-optimal contract exist (under which the buyer expects to exercise a positive number of options)? The simple answer to this question is that an agreement of concern is formed between the two parties whenever there are gains from trade. However, the seller-optimal contract will in general not realize all the available gains from trade, as a result of the seller's opportunistic behavior, which aims at extracting the maximum possible surplus from the buyer.

[9] By selecting a fixed-price contract with the all-inclusive tariff r the seller can effectively determine the buyer's demand Q, so that this problem can be rewritten in the form $\max_{Q\in[0,K]}\{\phi\lambda Q v_y(\lambda Q, D_0) - C(Q, \phi Q)\}$, this time under consideration of the boundary constraints imposed by $Q \in [0, K]$.

2.2 Socially optimal contracting

We now consider the choice of an option contract so as to maximize the buyer's and the seller's expected joint surplus. In what follows the latter is also referred to as "(expected) social welfare," even though the surplus of the downstream consumers and of the upstream suppliers, as well as that of ancillary agents (such as electricity providers) is not explicitly considered. In finding socially optimal (i.e., social-welfare-maximizing) contracts we maintain the assumption that the buyer and the seller retain full autonomy, in the sense that the seller still proposes a contract with parameters (p, s, K) and the buyer still first decides how many options Q to purchase, and, subsequently, how many options z to exercise, once the demand uncertainty has realized. We refer to a welfare-maximizing contract of this form as *ex-ante efficient* (or *ex-ante socially optimal*) contract.

An options contract is a form of coinsurance between the buyer and the seller. According to Borch (1962) an optimal coinsurance contract is such that the ratio of the buyer's and seller's marginal utilities are equalized across all states of nature. Therefore, if one party's expected marginal utility is constant, the other's must also be constant. If the seller is risk neutral, then her marginal utility is constant across states of nature, which implies "perfect insurance" for the risk-averse buyer with the seller taking on all of the risk. The interpretation of perfect insurance in this setting is that the buyer's marginal utility is also constant across states of nature. It is clear that despite this constancy at the margin, the buyer's absolute payoff may vary substantially across states, unless future contingencies become contractable (cf. Section 2.2.2)

2.2.1 Ex-ante efficient contract

Under an ex-ante socially optimal contract (p, s, K), the buyer solves (given any demand realization D) a second-period optimization problem of the form (1), to which the solution $z(Q, D, s)$ is given by Eq. 3. In the first period, the buyer decides about the quantity of options to purchase by solving the problem (5) with the same solution $Q(p, s, K)$ in (11) as under the seller-optimal contract. Hence, the expected social welfare as a function of the contract parameters is

$$\bar{W}(p, s, K) = \bar{V}(Q(p, s, K), s) + s\bar{z}(p, s, K) - C(Q(p, s, K), \bar{z}(p, s, K)), \tag{20}$$

where $\bar{V}$ and $\bar{z}$ are given by Eqs. 4 and 13, respectively.

Proposition 2 (Ex-ante welfare maximization) *An ex-ante socially optimal contract* (p, s, K) *is such that*

$$p = C_Q,$$
$$s = C_{\bar{z}},$$

and K is all of the seller's available capacity.[10]

From a social planner's perspective, it is ex-ante optimal to have the option contract directly reflect the seller's opportunity cost at the margin. The socially optimal base price p corresponds to the seller's cost of foregoing the use of the good in her own production process (e.g., due to long lead times). The socially optimal strike price compensates the seller for the marginal cost of not being able to use the good at short notice (e.g., for short-lead-time production or direct sale on a spot market). The seller-optimal option contract in Proposition 1 is generally inefficient, as it charges a base price above zero and also inflates the strike price over marginal cost, as established in Proposition 1. Because of the markup over marginal cost $C_{\bar{z}}$, a buyer tends to exercise an inefficiently small number of options. In the case of short production lead times (where $C_Q \approx 0$), which is of interest in the California water market, the base price is typically positive (i.e., above marginal cost), which implies that the buyer also acquires an inefficiently small number of options in the first place.

2.2.2 Ex-post efficient contract

In the absence of renegotiation in the second period, when uncertainty realizes, an option contract with a rigid strike price generically fails to implement an ex-post efficient allocation. Renegotiation is common practice in financial markets, where physical deliveries on contracts are rarely taken. Money is exchanged in the second period and the good is then sold on the market to the party with the highest second-period value. This guarantees that the good is allocated to the party valuing it the most, which is important, especially when transfers are costly due to transaction cost (e.g., through costly conveyance, transfer losses, or random delivery contingencies). In markets where physical delivery must be taken, a contract that may be ex-ante efficient will generally be ex-post inefficient.

An ex-post efficient contract is of the form (p, σ, K), where $\sigma(Q, D, m)$ is a *strike-price function* that implements a first-best exercise

$$z^{\mathrm{FB}}(Q, D, m) \in \arg \max_{z \in [0, Q]} \left\{ \hat{\phi} v(\lambda z, D) - c(Q, z, D, m) \right\}, \tag{21}$$

where $\hat{\phi}$ is either equal to ϕ or equal to one, depending on whether it is possible to make the option exercise contingent on delivery failure (by default in our model) or not.

[10] As pointed out in the proof of Proposition 2 (cf. Appendix), when $Q(p, s, K) \in \{0, K\}$ the option prices are generally not unique. Yet the socially optimal allocation remains unaffected by this generic multiplicity.

Hence, using the expression (3) for the buyer's optimal solution to his second-period problem, the strike-price function σ is implicitly defined through

$$z(Q, D, \sigma(Q, D, m)) = z^{\mathrm{FB}}(Q, D, m) = \sup\left\{q \in [0, Q] : \lambda\hat{\phi}v_y(\lambda q, D) \geq b(q, D, m)\right\}, \quad (22)$$

for any admissible $Q \in [0, D]$ and demand level D, where $b(Q, D, m) \equiv c_z(Q, z, D, m)$. An ex-post efficient base price p is such that it implements the first-best option-purchase quantity

$$Q^{\mathrm{FB}}(D, m) \in \arg\max_{Q\in[0,K]} \left\{\hat{\phi}v(\lambda z^{\mathrm{FB}}(Q, D, m), D) - c(Q, z^{\mathrm{FB}}(Q, D, m), D, m)\right\}. \quad (23)$$

Note that because of the state-contingency in the allocation we obtain optimal coinsurance according to Borch's rule, mentioned at the outset of this section. Without ex-post contingencies it is generally impossible to efficiently trade off the two parties' payoffs at the margin across all states of nature.

Proposition 3 (Ex-post welfare maximization) *An ex-post socially optimal contract* (p, σ, K) *is such that for all* $Q \in [0, K]$ *and all joint realizations* (D, m) *it is*

$$p = E\left[\left[\lambda\hat{\phi}v_y(\lambda Q^{\mathrm{FB}}(\tilde{D}, \tilde{m}), \tilde{D}) - c_Q(Q^{\mathrm{FB}}(\tilde{D}, \tilde{m}), Q^{\mathrm{FB}}(\tilde{D}, \tilde{m}), \tilde{D}, \tilde{m})\right]_+\right],$$

$$\sigma(Q, D, m) = b(z^{\mathrm{FB}}(Q, D, m), D, m) \quad (\equiv c_z(Q, z, D, m)),$$

and K *is the seller's available capacity, where* $z^{\mathrm{FB}}(Q, D, m)$ *and* $Q^{\mathrm{FB}}(D, m)$ *are solutions to (21) and (23), respectively.*

From Proposition 2, at a strike price of $s = C_{\bar{z}}$ the buyer will exercise options up to the point where his marginal value of execution is equal to the seller's *expected* marginal opportunity cost, plus the conveyance charge—and not the seller's actual opportunity cost. For instance, if the market price realizes above the expectation $\bar{m}$, then the buyer exercises too many options from a social welfare perspective. The seller's marginal value for the last option exercised is greater than the buyer's. If, on the other hand, the spot market realizes below $\bar{m}$, then—depending on Q—the buyer may exercise too few options.

2.3 Surplus extraction

The seller-optimal contract discussed in Section 2.1 extracts the buyer's surplus subject to the standard option-contract structure described by the tuple (p, s, K). It is clear that the seller can generally do even better by using a social-welfare-maximizing contract (as discussed in Section 2.2) and then extract all of the buyer's expected surplus by a (potentially negative) fixed transfer, from the buyer to the seller. This two-part tariff option contract ensures that the seller can extract the entire ex-ante surplus.

Since the buyer's reservation value is $\bar{V}_0$ as introduced after Eq. 4, the following result is immediate.

Proposition 4 (Surplus extraction) *A two-part tariff option contract (p, s, t, K), where $p = C_Q$, $s = C_{\bar{z}}$, $t = \bar{V}(Q(p, s, K), s) - \bar{V}_0$, and K is the seller's available capacity, is ex-ante socially optimal and extracts the buyer's entire expected surplus.*

The seller's reservation value is given by

$$\bar{\Pi}_0 = -E\left[c(0, 0, \tilde{D}, \tilde{m})\right] = -C(0, 0).$$

By adjusting the fixed transfer t in Proposition 4 between $t_{\min} = -pQ(p, s, K) - s\bar{z}(p, s, K) + C(Q(p, s, K), \bar{z}(p, s, K)) + \bar{\Pi}_0$ and $t_{\max} = \bar{V}(Q(p, s, K), s) - pQ(p, s, K) - \bar{V}_0$ it is possible to implement any individually-rational surplus distribution between the two parties. A necessary and sufficient condition for an option contract of the form (p, s, K) to exist is that there is an individually rational two-part tariff option contract (p, s, t, K) such that

$$t_{\min} \leq t \leq t_{\max}.$$

The inequality $t_{\min} \leq t \leq t_{\max}$ immediately implies the following existence result for an (individually rational) option contract (p, s, K). Equivalently, an individually rational two-part tariff option contract (p, s, t, K) exists if and only if the mean transfer $t = (t_{\max} - t_{\min})/2 \geq 0$.

Lemma 3 (Existence) *A (seller-optimal or socially optimal) option contract (p, s, K) is entered voluntarily by both parties if and only if*

$$\bar{V}(Q(p, s, K), s) + s\bar{z} - C(Q(p, s, K), \bar{z}(p, s, K)) \geq \bar{\Pi}_0 + \bar{V}_0,$$

where $Q(p, s, K)$ and $\bar{z}(p, s, K)$ are given by Eqs. 11 and 13, respectively.

Remark 3 In a dyadic relationship, where the two parties exert mutual influence, the distribution of bargaining power determines the split of surplus that the parties may agree to, provided that the inequality in Lemma 3 is satisfied. Assuming that the contract is binding at the outset and that there are no informational asymmetries, one may invoke cooperative bargaining theory (Roth 1979; Moulin 1988) to predict the outcome (e.g., the Nash bargaining solution). As is discussed at the beginning of Section 3, the prices obtained here provide an upper bound for what can be observed in the market, as the seller's bargaining power is limited for a variety of reasons. □

2.4 Parameter sensitivity

So far, the buyer's and seller's value functions were assumed fixed. However, due to changing economic conditions, e.g., because of an increase in energy prices or technological innovation, these values may be subject to substantial changes. It is therefore useful to examine the influence of parameter dependencies. For this, we assume that the buyer's value function is of the form $\hat{v}(y, D, \alpha)$, where α is a real-valued parameter.[11] Similarly, we assume that the seller's cost function is of the form $\hat{c}(Q, z, D, m, \gamma)$, where γ is a real-valued parameter.

For the sake of discussion let us focus on the case where the buyer has an option of buying the good from an alternative source at the price α. In that case, before exercising any option contract he determines

$$\hat{v}(\lambda z, D, \alpha) = \max_{x \geq 0} \{v(\lambda z + x, D) - \alpha x\}.$$

Using the envelope theorem in the same manner as before we can compute the variation of $\hat{v}$ with respect to the outside price,

$$\hat{v}_\alpha(y, D, \alpha) = -\sup\left\{\xi \geq 0 : v_y(y + \xi, D) \geq \alpha\right\} \leq 0.$$

It is easy to show that $\hat{v}_{y\alpha} = \xi'(\alpha) \leq 0$, so that $\hat{v}(y, D, \alpha)$ is submodular in (y, α).[12]

Proposition 5 (Contract sensitivity) *Let $\hat{c}$ be such that $\hat{c}_{zz}, \hat{c}_{QQ}, \hat{c}_{Qz} \geq 0$.*[13] *(i) If $\hat{v}$ is submodular in (y, α), then the socially optimal option-contract parameters $p(\alpha), s(\alpha)$ are nondecreasing in α. (ii) If $\hat{c}$ is supermodular in (Q, z, γ), then the socially optimal option-contract parameters $p(\gamma), s(\gamma)$ are nondecreasing in γ.*

The actual change in the contract size under an increase in the parameters α or γ depends on the dominance of two forces. An increase in the price of the outside option will encourage the buyer to hold more options. However, in recognition of this fact, the seller will increase prices, which in turn lowers the demand for options.

The question remains as to how the seller's ability to extract surplus is influenced by changes in the parameter α or the parameter γ. For this we can turn to the revenue-maximizing two-part tariff contract (p, s, t, K) and note that the comparative statics of p and s with respect to α, γ are identical to the socially optimal contract. The dependence of the fixed transfer t on α is obtained by the envelope theorem,

$$t_\alpha = \left(\bar{V} - \bar{V}_0\right)_\alpha = E\left[\hat{v}_\alpha(\lambda z, \tilde{D}, \alpha) - \hat{v}_\alpha(0, \tilde{D}, \alpha)\right] \leq 0,$$

[11] The discussion in this section also applies, with minor changes, when parameters are vector-valued.

[12] The concept of supermodularity (or submodularity) is of great importance to establish monotone comparative statics, as it provides necessary and (in some sense also sufficient) conditions for solutions to an equilibrium or optimization problem to have a monotone dependence on parameters [see, e.g., Milgrom and Shannon (1994); Topkis (1998), and, for a generalization, Strulovici and Weber (2008)].

[13] Under our quasi-linearity assumption that $\hat{c}(Q, z, D, m, \gamma) = \hat{a}(Q, D, m, \gamma) + \hat{b}(Q, D, m, \gamma)z$ this is satisfied if $\hat{b}$ is nondecreasing in Q.

provided that $\hat{v}$ is submodular in (y, α). Hence, for example, as the buyer's price of his outside option increases, the fixed transfer from the buyer to the seller cannot increase. This makes sense, as the buyer's expected surplus drops when the attractiveness of his outside option diminishes. From the envelope theorem we also infer that the fixed transfer t does not depend on γ at all. Nonetheless, a change in γ can influence the existence of a contract (cf. Lemma 3).

2.5 Simple model parametrizations

For certain specifications of the option pricing model it is possible to obtain more concrete insights. Below we discuss simple linear and quadratic versions of the model. The linear version of the model is applied to the California water market in Section 3.

2.5.1 Linear cost

If the buyer's second-period holding and shortage cost are constant at the margin, his payoff function is of the form

$$v(y, D) = -\left(\beta_1[D - y]_+ + \beta_2[y - D]_+\right), \tag{24}$$

where β_1 denotes the shortage cost, and β_2 the holding (or storage) cost associated with consuming a quantity y of the good given the demand realization D. From Eq. 3 we obtain the buyer's optimal exercise quantity $z(Q, D, s) = \mathbf{1}_{\{s \leq \lambda\beta_1\}} \min\{D/\lambda, Q\}$. Thus, by Eq. 13 the buyer's expected second-period demand can be written in the form

$$\bar{z}(p, s, K) = \left(\frac{1}{\lambda} E\left[\tilde{D} \,\middle|\, \tilde{D} \leq \lambda Q(p, s, K)\right] + Q(p, s, K)\right)\left(1 - F(\lambda Q(p, s, K))\right),$$

where the buyer's first-period demand for options is, using Eq. 11,[14]

$$Q(p, s, K) = \begin{cases} \min\left\{K, \frac{1}{\lambda} F^{-1}\left(1 - \frac{p}{\phi(\lambda\beta_1 - s)}\right)\right\}, & \text{if } (p/\phi) + s \leq \lambda\beta_1, \\ 0, & \text{otherwise.} \end{cases}$$

The last expression has a singularity at the price tuple $(p, s) = (0, \lambda\beta_1)$, at which the buyer can be "convinced" (at least approximately, through appropriate limiting processes in p and s) to buy *any* given quantity Q_0 between zero and K. This will lead to a profit-maximizing contract for the seller, as long as $\lambda\beta_1$ exceeds the seller's marginal cost $C_{\bar{z}}(Q_0, z) \equiv B(Q_0) \in [B(0), B(K)]$.

[14] The buyer solves the well-known newsvendor problem (see, e.g., Petruzzi and Dada 1999 for an overview), the first analyses of which date back to Edgeworth (1888) in economics and Whitin (1955) in management science.

2.5.2 Quadratic cost

Consider now a buyer who faces a nonlinear (quadratic) underage cost and an outside supply, of unit price α, so that (using the formulation in Section 2.4)

$$v(y, D) = \max_{x \geq 0} \left\{ -\frac{\beta}{2} \left([D - y - x]_+ \right)^2 - \alpha x \right\}$$
$$= \begin{cases} -\frac{\beta}{2} \left([D - y]_+ \right)^2, & \text{if } D - y < \frac{\alpha}{\beta}, \\ -\alpha (D - y - \frac{\alpha}{2\beta}), & \text{otherwise,} \end{cases}$$

where α, β are positive constants. Clearly, if the cost α is large compared to the shortage-cost coefficient β, the outside supply is not used at all. In case it is used, however, the problem becomes quasi-linear in y. From Eq. 3 we find the buyer's second-period demand,

$$z(Q, D, s) = \mathbf{1}_{\{s \leq \lambda\alpha\}} \min \left\{ Q, \frac{1}{\lambda} \left[D - \frac{s}{\lambda\beta} \right]_+ \right\}.$$

Since $\kappa(Q, D, s) = \mathbf{1}_{\{s \leq \lambda\alpha\}} \left[\lambda\beta [D - \lambda Q]_+ - s \right]_+$, we have by Eq. 9 that

$$\bar{\kappa}(Q, s) = \mathbf{1}_{\{s \leq \lambda\alpha\}} \left(\lambda\beta \left(E \left[\tilde{D} \,\middle|\, \tilde{D} \geq \lambda Q + \frac{s}{\lambda\beta} \right] - \lambda Q \right) - s \right) \left(1 - F(\lambda Q + \frac{s}{\lambda\beta}) \right).$$

If the buyer's first-period demand $Q(p, s, K)$ is strictly between zero and K, then by Eq. 11 we must have that

$$\phi\bar{\kappa}(Q, s) = p.$$

Numerical example. Using the above quadratic specification of the buyer's value function, and assuming that the downstream demand is uniformly distributed on $[0, 1]$, the buyer's (interior) options demand $Q(p, s, K; \alpha) \in (0, K)$ can be determined explicitly as follows:

$$Q(p, s, K; \alpha) = \mathbf{1}_{\{s \leq \lambda\alpha\}} \frac{1}{\lambda} \left[1 - \frac{2p}{\lambda\beta} - \frac{s}{\lambda\beta} \right]_+.$$

When the buyer has an outside supply option available at a fixed price α, the seller is constrained to charge a strike price below α. As the seller, who is assumed to have the second cost structure discussed in Remark 1 (with $\bar{c} = w = 0$ and $\bar{m} = 0.5$), expects to make $\bar{m}$ per unit of supply by selling onto the spot market, there is no contracting when $\alpha < \bar{m}$. There is a kink in the demand function at the point where $\min\{\bar{D}(Q, s; \alpha), 1\} = 1$. Indeed, for $K = \lambda = 1$ and $\beta = 2$ the inequality

$$\bar{D}(Q, s; \alpha) = Q + \frac{\alpha}{2} = 1 - \sqrt{p} - \frac{s}{2} + \frac{\alpha}{2} > 1$$

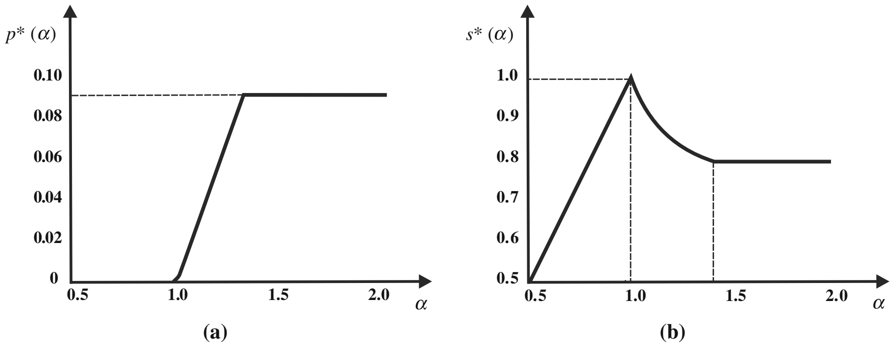
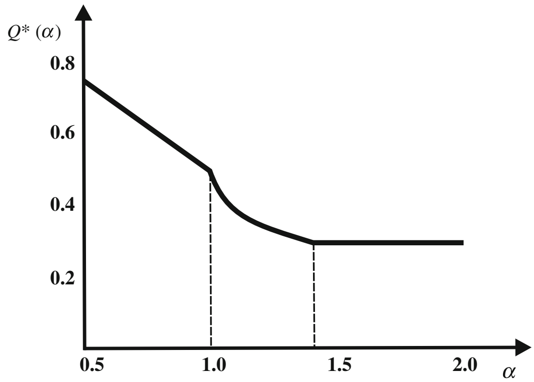


Fig. 1 Dependence of option prices on buyer's outside supply cost α

Fig. 2 Optimal option contract volume as a function of α



implies that

$$2\sqrt{p} + s < \alpha. \tag{25}$$

For prices satisfying inequality (25) the buyer does not expect to ever rely on his outside option. Figure 1 shows the seller-optimal prices $p^*(\alpha)$ and $s^*(\alpha)$ as a function of the outside option price α. For low values of the outside option, the seller charges the price pair $(0, \alpha)$. This coincides with the ex-ante socially optimal price structure. Hence, the presence of an outside supply option can induce the socially optimal behavior if its price α is sufficiently low. As α increases, the outside option eventually becomes too expensive to rely on. Figure 2 illustrates the optimal contract volume $Q^*(\alpha) = Q(p^*(\alpha), s^*(\alpha), 1; \alpha)$ as a function of α, which is decreasing.

3 Application to the California water sector

The California water market is characterized by a number of market imperfections. With no formal marketplace, the search costs incurred in the matching phase are fairly high. In addition, limited access to infrastructure and the existing heterogeneity amongst sellers, e.g., sellers with different crop regimes and therefore different marginal products of water, limit the pool of potential contractors. As such, bilateral contracting arises naturally, when a buyer and seller are each others' only alternative for a relevant trading partner.[15] Thus, most market transactions in today's water market are accurately captured by a simple bilateral contracting model. Bilateral contracting also occurs in a number of other imperfect markets, such as electricity (Wu et al. 2002).

Using data from the bilateral contracting that has taken place to date in the California water market, we estimate relative welfare gains of between two and three percent. For policy makers assessing the value of a contract market for water, this is an important point of departure. The seller's expected value, as articulated in Section 2, depends on the probability of an infrastructure failure, the expected spot market price for her production good (her crop), the production lead time, the transport cost of water, and the buyer's demand at the set contract prices. The buyer's expected value depends also on the probability of infrastructure failure and on his second-period payoff function from delivering water to meet uncertain downstream demand, and clearly the base and strike prices.

The prices we estimate are based on the seller's making take-it-or-leave-it offers. Alternative pricing and allocation rules are not treated explicitly. We do not suggest that the prices in the seller-set model, e.g., where the seller retains all the bargaining power, are fully predictive. Instead, they serve as an upper bound on any rational contract prices. Lower market prices reflect buyer bargaining power. In addition, informational asymmetries may, at least theoretically, make it useful for the seller to consider a nonlinear pricing scheme which provides incentives for information revelation by leaving an information rent to the buyer, thus also resulting in lower prices. Hence, the seller-set prices can be used as a benchmark for analyzing buyer bargaining power. Models that estimate prices under different bargaining protocols would be useful for investigating the range of likely outcomes in the future. In addition, models that capture the dynamics of the matching phase will be increasingly relevant as the water market expands. The variant of the bilateral option contracting model that captures the presence of an outside option is a first step in this direction, as the outside option could be an alternative contract price, which in turn impacts the prices that the seller can charge. There are also alternative contract features that merit investigation from a welfare standpoint. For instance, the risk of conveyance loss could be shared between the buyer and the seller.

As discussed in Section 1, option contracts in the California water market serve as a mechanism through which water intermediaries can coordinate uncertain supply and

[15] Over time, matching could be facilitated by the introduction of an electronic marketplace and tradeable infrastructure rights, combined with expansion of state water infrastructure (Tomkins et al. 2008). The available benefits from contracting suggest significant welfare gains to society. Overall welfare is weakly increasing in the number of market participants and under improved matching. As the market grows and bilateral contracting gives way to multilateral contracting or an electronic marketplace, models that capture strategic interactions between participants will be increasingly important. This is an area for future investigation.

demand in dry years.[16] The contracts signed to date between a water intermediary (e.g., MWD) and an agricultural water district have usually specified the fallowing of rice acreage in exchange for a strike payment per acre-foot of conserved water. The conserved water to be made available for transfer to the intermediary is calculated based on consumptive crop use (defined as "evapotranspirative use," i.e., the estimated volume of water absorbed by the plant and evaporated from the plant and land surface) and is distinct from the total amount of water applied to the crop.[17] The seller's expected value from contracting is a combination of his revenue from the sale of the options and his expected revenue from both the exercise of the options and the offload of excess supply onto the commodity market. The seller's reservation value is the expected revenue from applying the water to cultivate his rice crop and offloading the entire crop yield, or supply, onto the market.

3.1 Model identification

The seller's value and cost are specified by Eqs. 15 and 19, respectively. The cost specification assumes that the seller can use productively all of the water not called under the contract, so that

$$C(Q, \bar{z}) = -(\bar{m} - \bar{c})(K - \bar{z}) + w\bar{z}, \tag{26}$$

where $\bar{m} - \bar{c}$ is the marginal product of water for a crop (here rice).[18] Table 1 reports the marginal product (MP) of water for rice in 2008 based on the production cost per acre of rice—as reported in recent USDA farm surveys—the yield per acre of cultivated rice, as estimated by the USDA, and the consumptive-use calculation provided by the California Department of Water Resources (DWR).[19] Regarding price expectations, each year farmers have a choice to sign a contract with a rice marketer even before

[16] In the spring of 2003, the Metropolitan Water District (MWD) called options from 10 of 11 contracts signed that year, for a net supply of 126,230 af—a volume of water approximately equal to 5% of MWD's average annual deliveries of two million acre-feet (maf), and just above the 100,000 af supplied under the long-term transfer between MWD and IID. In 2005, MWD signed contracts in 2005 with Glenn–Colusa Irrigation District, Western Canal Water District, and Richvale Irrigation District, all of which were party to the 2003 contracts. None of these options were ever called, with spring rains alleviating the water shortage. The total volume of water under contract was 127,275 af. Of this total, 14,780 af was contracted for by other State Water Project contractors, with the rest of the options held by MWD. In the spring of 2008, San Diego County Water Authority (SDCWA) called options from two contracts, for a net supply of just over 24,000 af. The contracts, signed at the beginning of March, specified a $10/af base to reserve the rights to the water through April 2, on which date SDCWA faced a decision about whether or not to extend the option for $40/af. The execution date was set for April 15, with a strike price of $200/af. The strike price was more than double that set in the MWD contracts (of $90/af). SDCWA extended and executed all of the options.

[17] The difference in volume between consumptive use and applied use is the volume of water that returns to the environment in the form of runoff or recharge.

[18] More precisely, $\bar{m} - \bar{c}$ is the average contribution of water (ACW) to profit, as there are more than one production input, including, for example, fertilizer, labor, and the (opportunity cost of the) agricultural land being used.

[19] The average cost per acre of rice cultivation for 2003 and 2005 is based on the reported cost in 2000. The range of rice prices reported in Table 1 are based on market prices reported by the Farm Service for 2008.

Table 1 Rice production data (DWR 2008; FAO 2008; Livezey and Foreman 2004; USDA 2008)

Parameter	Unit	2003 Estimate	2005 Estimate	2008 Estimate/range
Price	\$/cwt	6.25	7.63	13.5–19
Subsidy	\$/cwt	2.35	2.35	2.35
Yield	cwt/acre	71.6	71.6	71.6
Revenue	\$/acre	616	715	1,133–1,527
Average cost	\$/acre	479	479	833
Profit	\$/acre	137	236	300–694
Water use	af/acre	3.3	3.3	3.3
MP of water	\$/af	41	71	91–210

planting, which locks in a payment per hundredweight (cwt) of rice.[20] Alternatively, farmers can join a marketing cooperative and receive monthly installments from coop sales. A third option for the farmers is to wait until harvest and then sell the rice directly to a marketer at the current price or pay storage fees and offload the rice onto the market at a later date.

The value function of the water agency (the buyer), given in Eq. 4, depends on four factors: the distribution of excess downstream demand for water, the shortage cost of water, the conveyance cost and losses, and the probability of contract non-fulfillment. A linear specification for the shortage cost, as detailed in Section 2.5, serves as an approximation for urban water agencies in California, which face a constant marginal cost per acre-foot for additional supply. Urban water agencies in Southern California can, for example, acquire additional supply from MWD in times of shortage at a "penalty rate" of \$1,347/af (in 2008). The actual cost depends on whether a shortage is covered by the water agency through a secondary (and presumably more expensive) supply source or whether it is passed on directly to consumers. SDCWA has a policy to meet excess retail demand through additional water purchases, i.e., purchases at the "penalty rate" from MWD. The penalty rate, well above the regular Tier 1 rate that MWD charges its member agencies for contracted supply, is in effect for supply requests above the contracted level.[21] The MWD penalty rate is a proxy for the market rate for an extra acre-foot of supply. In the presence of an alternative supply technology, a possible proxy for the shortage cost might be the cost per acre-foot of supply via this alternative technology, e.g., desalination, which is currently estimated at \$800–900/af. If, rather than cover the excess demand, SDCWA planned to pass the shortage on directly to consumers, the estimate for the shortage cost would need to take into account the loss in consumer welfare, as well as the cost of a "water outage," including business-interruption and landscape losses. A comprehensive study in 1993, commissioned by SDCWA and conducted by the economic consulting firm CIC, Inc., reported high sectoral shortage costs that, when aggregated, totaled \$5,554/af. As

[20] In the U.S., 1 cwt = 100 lbs ≈45.359 kg.

[21] The penalty rate is technically only in effect once the member agency exceeds contracted deliveries by more than 10%.

Table 2 Contract parameters (S. Hirsch [MWD], personal communication; MWD 2008; Campbell and Hess 2008)

Parameter	Unit	2003 Estimate	2005 Estimate	2008 Estimate
Loss coefficient (λ)	%	80	80	80
Probability of NF (ϕ)	%	50	50	50
Shortage coefficient (β_1)	\$/af	1, 347	1, 347	1, 347
Demand distribution	uniform (on)	[0,146,230]	[0,127,275]	[0,24,038]
MP of water ($\bar{m} - \bar{c}$)	\$/af (base)	42	71	151
Wheeling cost (w)	\$/af	253	258	278
Seller capacity (K)	af	146,230	127,275	24,038

discussed in Section 2.5, a constant shortage cost implies that the buyer fully covers excess demand when there is available supply to do so. In other words, the buyer exercises all options up to the realized demand level D, assuming fulfillment is possible. Furthermore, the seller optimally charges a price pair $(0, \lambda\beta_1)$.

Table 2 reports the parameters for the buyer's and seller's value functions used to estimate the social welfare gains under contracting in 2003, 2005, and 2008. Losses are assumed to be uniformly distributed, with the upper bound of demand based on the actual yearly contract size. The actual excess demand distribution assessed by the contracting agencies is not reported in the contracts signed to date.[22]

There is a high probability of non-conveyance, or non-fulfillment (NF). SDCWA reports assessing a 50% probability that the San Francisco Bay Delta pumping plant will be over-capacitated at any given time, restricting the movement of water north–south (SDCWA 2008a,b).[23] If conveyance is possible, there is a standard charge per-acre-foot conveyed. The unbundled MWD wheeling rate consists of three parts as reported in Table 3. The first two fees are levied by the State Water Project for use of the infrastructure, which they control, and the third is an environmental surcharge levied by MWD. The current system power rate of \$110/af reflects an electricity cost of \$0.05/kWh. The power contracts, negotiated by the Department of Water Resources, are for large volumes of power and have been price-stable in the past. North–south conveyance requires an average of 2,200 kWh of electricity per acre-foot, which includes the energy to pump the water south over the Tehachapi Mountains via a series of lifting stations. The system access charge is levied to recoup the infrastructure cost. In

22 There are three reasons for the dramatic decrease of the seller capacity in 2008 compared to previous years: storage levels, weather conditions, and competition for the available water. In 2008, storage levels were high, precipitation forecasts positive, and MWD lost several contracts due to the fact that other water districts were willing to procure water at a relatively high price.

23 The risk of non-conveyance, or non-delivery, was purely an infrastructure risk. The contracts specified that the water to be made available through fallowing arrangements was to be water to which pre-1914 water rights were held. Under the California Water Code, pre-1914 water rights are the most senior water rights. As such, they are considered firm rights: there is always enough water in the system to ensure that priority rights holders receive their allocation, with junior rights holds entitled to the rest of the annual supply, in order of priority.

Table 3 MWD's unbundled wheeling charges (per af)

Year	Access charge	Stewardship charge	System power charge	Total
2003	\$141	\$23	\$89	\$253
2005	\$152	\$25	\$81	\$258
2008	\$145	\$25	\$110	\$278

addition, there is an associated conveyance loss. The 2003, 2005, and 2008 contracts (the volumes of which are given in Table 4) all specified that the conveyance losses associated with transferring water would be borne by the buyer, as would the cost of conveyance. The north–south transfer of water via the San Francisco Bay Delta results in significant conveyance losses, estimated at 20% (MWD 2008), due to the need for retention of a percentage of transferred water ("carriage water") to meet Delta water quality standards.

3.2 Welfare gains under option contracting

The social welfare gain under a contract (p, s, K) is

$$\bar{V}(Q(p, s, K), s) + s\bar{z} - C(Q(p, s, K), \bar{z}(p, s, K)) - \bar{\Pi}_0 - \bar{V}_0, \tag{27}$$

where $C(Q(p, s, K), \bar{z}(p, s, K))$ is given in Eq. 26, $Q(p, s, K) = K$ (for all $s \leq \lambda\beta_1$), and $\bar{z}(p, s, K) = \phi K$. Table 5 below reports the expected (ex-ante) social welfare gains under contracting in 2003, 2005, and 2008 for three possible price expectations (low, base, and high), with the parameters as specified in Table 3. The farmers' expectations for the 2003, 2005, and 2008 commodity prices are unrecorded; therefore, historical prices for rice as reported by the Food and Agriculture Organization of the United Nations (FAO) are used in the base case in 2003 and 2005. The 'low' scenario reflects an underestimate of the actual price by 25%, and the 'high' scenario reflects an over-estimate, also by 25%.

As the expected commodity price increases, boosting the reservation values, the sellers' surplus from trade is slowly eroded. The estimated social welfare gains are

Table 4 Historical contract types and transfer volumes

Year	Buyer	Contract Type	Volume (af)	Execution (af)
2003	MWD	Options	146, 230	126, 230
2005	MWD	Options	112, 495	0
2005	Other SWP contractors	Options	14, 780	0
2008	MWD	Direct purchase	28, 674	28, 674
2008	Other SWP contractors	Direct purchase	13, 493	13, 493
2008	SDCWA	Options	24, 038	24, 038

SWP State Water Project

highest in the low-price case. In 2003, the average price of rice for U.S. producers was $6.25; in 2005, it was $7.26 (FAO 2008). The 2008 prices are based on predicted market prices, as reported by the U.S. Farm Service. The federal subsidy on rice production of $2.35/cwt, reported in Table 2, is also included in the calculations. The social welfare gains in 2003 and 2005 are estimated to be upwards of $33 and $27 M, respectively. Notably, the anticipated gains in 2008 are significantly smaller due to a reduction in the size of the contracts.

3.3 Price trends

It appears that past contract prices have been highly favorable to the buyer. There are three likely explanations for this fact. The first explanation is that of buyer bargaining power. Insofar as the division of surplus is an indication of bargaining power, the calculations in Table 5 suggest that MWD was in the stronger position. The second explanation is one of informational asymmetry: if sellers were unaware of the true value of the options to the buyer, they may have settled for lower prices, leaving a buyer of 'higher-than-expected' demand with an information rent. Lastly, changes in the modelling assumptions regarding the actual shortage cost of water, the distribution of excess demand faced by the buyer, the seller's expected commodity price, and both the cost and probability of conveyance, as well as the one-shot nature of contracting, would all impact the estimates in Table 5.

While the sellers collectively had an estimated expected surplus of between $1.8 and $3.3 M in 2003, MWD appropriated nearly 90% of the total surplus, or $31.4 M. There are two important factors worth noting with regard to MWD's bargaining power. The first is that MWD initiated the contracts, contacting farmers regarding the sale of options on their water. As such, MWD was also in the position to make the first offer. If MWD credibly conveyed the threat to leave negotiations at any point, the sellers may have faced an "accept/reject" offer with "accept" as the higher-value choice, yielding a payoff above their reservation values. A second factor acknowledges the political power held by the institutions involved in the transactions. MWD has 26 Southern California member agencies, including the utilities of the state's two largest cities, Los Angeles and San Diego. The political power in these two constituencies alone is considerable. Wherever there exists an imbalance of political power, there also exists an implicit threat of political recourse. In California, the implicit threat is that of an involuntary reallocation of water. Agricultural water rights could be challenged

Table 5 Surplus division and social welfare gain with option contracts

Year	2003			2005			2008		
Surplus	Low	Base	High	Low	Base	High	Low	Base	High
Buyer (%)	90.6	92.6	94.6	90	90.3	95.2	66.9	70	73.4
Seller (%)	9.4	7.4	5.7	10	9.7	4.8	33.1	30	26.6
Total (M$)	34.7	34	33.2	29.1	29	27.5	4.81	4.59	4.37

on efficiency grounds, as they were in IID, or water could be confiscated based on an argument for the primacy of human (urban) use, as has been done in other states (notably New Mexico).[24]

Related to the issue of buyer bargaining power is that of informational asymmetry. While information regarding water management in California is ostensibly public information—urban an agricultural water providers in the state are all public intermediaries—an urban water agency such as MWD has some degree of operational flexibility, making the quantification of both excess demand and the true shortage cost of water difficult for an outside entity to estimate. For example, an urban water agency may elect to draw down storage in a given year as opposed to relying on outside water purchases to meet excess demand. There may also be additional transfer options from competing sellers. Finally, there is the possibility of rationing, with the associated implied consumer surplus losses and implementation costs.

The prices in the 2008 SDCWA contracts were higher than those in the 2003 and 2005 contracts signed by MWD. Part of the explanation for the increase in price owes to an increase in the seller's reservation value. The price of rice on the global exchange increased fivefold between 2007 and 2008. At a contract offer of $10/af upfront and $90/af upon exercise, a seller would prefer to cultivate rice than to contract his water. Hence, prices necessarily adjusted upward to meet the seller's rationality constraint. Nonetheless, a comparison of the sellers' expected surplus in 2003 and 2005 to that under the 2008 contracts lends credence to the argument that there has also be an increase in seller power. The percent of the expected social surplus received by the sellers increased from less than 10% in 2003 and 2005 to above 30% in 2008.

The increase in seller power may be attributed in part to buyer competition. Not only did SDCWA enter the option market for the first time, but there were also a number of agricultural water districts looking to buy, willing to bid up the price of water for application to other high-value crops. Higher contract prices may also result from a reduction of informational asymmetry. As information regarding the high cost of urban water shortage was disseminated, sellers may have adjusted their price estimates.

4 Conclusion

As Adler (2008) points out, "[t]here is an urgent need to develop more extensive market institutions to manage water supplies" (p. 17). Option contracts implementing temporary resource transfers can facilitate gains from trade that might go unrealized if only permanent transfers of water rights were possible. Temporary transfers can lower the institutional resistance and transaction cost of permanent transfers, enhancing the feasibility of trade. The California water sector has encountered market frictions in the form of both institutional resistance and high transaction cost associated with permanent water rights transfers. The success of temporary water transfers in the state in recent years highlights the potential of option contracting to create a more

24 Under the California Water Code, retention of a water right requires "beneficial use" of the water. Water rights can therefore be confiscated, or amended, if the water associated with the right is being wastefully applied. This particularly applies to agricultural users, who may be using outmoded irrigation techniques.

active water market. The fact that transfer agreements were renewed in 2005 and 2008 suggests the economic viability of option contracting.

Thus far, activity in the California water market has been fairly limited. Prerequisites for a more active water market include reliable access to infrastructure and a centralized trading platform that would further reduce buyer–seller matching costs (Tomkins et al. 2008). Current access to infrastructure is granted on a priority basis. Marketable infrastructure access permits would allow users with higher valuations to bid for (and acquire) access. An effective, decentralized trading system could be jump-started through the issuance of tradeable block permits to water districts, with each permit specifying a time, region of access, and standard volume of water.[25] Limited infrastructure capacity would still clearly impede trade in such a system. Addressing the capacity issue requires construction of additional transport or storage infrastructure, where in the case of the latter the timing of water transfers on existing infrastructure could be adjusted to increase system throughout. As suggested by a referee, the valuation information provided by an active contract and options market could facilitate the decisions to invest in further storage and interregional conveyance capacities.

Block permits for infrastructure access could be traded in a centralized (e.g., online) marketplace that can serve for trading the actual option contracts. Examples of active online marketplaces can be found in consumer goods, timber, and electric power. Water transfers would still be subject to environmental review and government oversight. The degree to which these portions of the transfer process can be streamlined is an important determinant for market liquidity. Short-term water transfers, e.g., transfers arranged for a single year, currently enjoy expedited review in California. If subject to the same full review under the California Environmental Quality Act (CEQA) currently required of long-term water transfers, such transfers would no longer be viable for covering near-term supply shortages. To the extent that environmental reviews could be conducted in advance and standing permission for transfers granted, transfers could still be arranged on short notice and used to cover near-term supply shortages.

As the water market expands, the design of contracts becomes an increasingly important matter. Reforms in current design can lead to a more efficient contract market. As discussed in Section 2.2, seller-set contracts levying a positive upfront charge per option (base price) are inefficient if it is not set at the actual opportunity cost of committing the contracted volume (Proposition 2). The latter is close to zero, due to customary timing of option exercise which leaves the seller with enough flexibility to use unclaimed water for her own crop production. The seller-optimal strike price tends to be above the marginal cost for the seller to provide the water covered by the option contract, in contrast to Wu et al. (2002) (cf. the discussion after Proposition 1). In subsequent work, Wu and Kleindorfer (2005) indicate that in the context of their model (which contains an active spot market), competition among buyers and sellers is likely to increase the efficiency of option contracts. Extending our model to a setting with multiple buyers and sellers, in the spirit of Mendelson and Tunca (2007), is subject to further research.

[25] The state and federal government own and operate much of the state's critical infrastructure. There is some local and regional control, e.g., the L.A. aqueduct.

As established in Section 2.3, the seller can use a fixed transfer instead of a volumetric base price to extract surplus and at the same time implement an ex-ante efficient allocation of water. Contracts structured to specify a fixed upfront fee for contracting and a strike price per option will tend to be more efficient, where the efficiency properties of an option contract are reflected in the actual strike price charged. Market indexing of options can further increase efficiency through the ex-post transfers based on the realization of relevant uncertainties. While the buyer's demand realization may not be fully contractable due to limitations concerning its observability and verifiability, the seller's outside market prices for crops and water could in many cases be used for indexing.

The issues discussed in this paper are broadly applicable to developing water markets worldwide, e.g., in Australia (ACCC 2008). A move to a more active trading regime can be expected as the increased variability and reduced availability of water continue to drive its scarcity and increase in value. Furthermore, the infrastructure investment required for providing the necessary conveyance capacity for the transfers can be expected to decrease in significance relative to the expected gains from improved allocative efficiency and risk management.

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Appendix: Proofs

Proof of Lemma 1 From Eq. 11 we obtain immediately that $Q(p, s, K)$ is nonincreasing in $-K$. Regarding the monotonicity of the buyer's demand for options, consider first the interior case where $0 < Q(p, s, K) < K$. Equation 11 implies that

$$\phi\bar{\kappa}(Q(p, s, K), s) = p.$$

The relations in (12) then follow immediately by differentiating the last equality implicitly with respect to p and s, respectively, taking into account (2) and (9). In the case where $Q(p, s, K) = 0$, the previous inequalities imply that demand cannot take a positive value for any $(\hat{p}, \hat{s}) > (p, s)$. Lastly, in the case where $Q(p, s, K) = K$, demand cannot increase as a direct consequence of Eq. 11, restricting it to the interval $[0, K]$. □

Proof of Lemma 2 Note first that Eq. 13 immediately implies that $\bar{z}$ is nonincreasing in $-K$. The buyer's expected exercise volume as a function of the contract-parameter tuple (p, s, K) is

$$\bar{z}(p,s,K)=\phi\left((1-F(\bar{D}))Q(p,s,K)+\int_{\underline{D}}^{\bar{D}} z(Q(p,s,K),D,s)dF(D)\right) \tag{28}$$

where the threshold levels $\bar{D}=\bar{D}(Q(p,s,K),s)$ and $\underline{D}=\underline{D}(s)$ are defined in Eqs. 7 and 8, respectively. By differentiating both sides of Eq. 28 with respect to p and s, and using the fact that by Lemma 1 it is $Q_p, Q_s<0$, we obtain the results in (14) as long as $0<\bar{z}(p,s,K)<K$. Note that

$$0<\delta=\frac{\int_{\underline{D}}^{\bar{D}} z_s(Q,D,s)dF(D)}{\bar{z}_s}=\frac{\int_{\underline{D}}^{\bar{D}} z_s(Q,D,s)dF(D)}{\phi(1-F(\bar{D}))Q_s+\int_{\underline{D}}^{\bar{D}} z_s(Q,D,s)dF(D)}<1,$$

since $z_s<0$ on $[\underline{D},\bar{D}]$, and thus $\bar{z}_s<0$. The situations in which $\bar{z}(p,s,K)\in\{0,K\}$ are treated analogously to the boundary cases in the proof of Lemma 1. □

Proof of Proposition 1 The first-order necessary optimality conditions with respect to the base price p and the strike price s in the seller-optimal pricing problem (15) are

$$\begin{aligned} pQ_p+Q+s\bar{z}_p-C_QQ_p-C_{\bar{z}}\bar{z}_p&=(\mu-\nu)Q_p,\\ pQ_s+\bar{z}+s\bar{z}_s-C_QQ_s-C_{\bar{z}}\bar{z}_s&=(\mu-\nu)Q_s,\end{aligned}$$

where μ,ν are the Lagrange multipliers associated with the constraints $Q\le K$ and $Q\ge 0$, respectively. Using the direct relation between (Q_p,Q_s) and $(\bar{z}_p,\bar{z}_s)$ provided in Lemma 2, these two equations are equivalent to

$$\frac{p-C_Q+\phi(1-F(\bar{D}))(s-C_{\bar{z}})}{p}=\frac{1}{\varepsilon_p}+\frac{\mu-\nu}{p} \tag{29}$$

and

$$\frac{s-C_{\bar{z}}+\frac{1-\delta}{\phi(1-F(\bar{D}))}(p-C_Q)}{s}=\frac{1}{\varepsilon_s}+\frac{1-\delta}{\phi(1-F(\bar{D}))}\frac{\mu-\nu}{s}, \tag{30}$$

where $\delta,\varepsilon_p,\varepsilon_s$ are as in Lemma 2. When $0<Q(p,s,K)<K$, the expressions for p,s in part (i) of the proposition follow as the unique solution to the linear system of equations 29–30 with $\mu=\nu=0$. In the case where $Q(p,s,K)=K$, it is $\nu=0$ and, by Eq. 9, $\phi\bar{\kappa}(K,s)=p$. Similarly, in the case where $Q(p,s,K)=0$, it is $\mu=0$ and $\phi\bar{\kappa}(0,s)=p$. The equalities in part (ii) obtain by substituting $p=\phi\bar{\kappa}(q,s)$ for $q\in\{0,K\}$ in Eqs. 29–30 and eliminating the Lagrange multipliers (one of which is zero).

The inequalities in parts (i) and (ii) follow from the fact that $p = \bar{\kappa}(Q, s)$, which implies that p is nonnegative, and that, by virtue of Eqs. 28–30 and Lemma 2,

$$\delta\,(s - C_{\bar{z}}) = \left(-\frac{\bar{z}}{\bar{z}_s}\right)\left(1 - \frac{\phi(1 - F(\bar{D}))Q}{\bar{z}}\right) \geq 0,$$

which implies that $s \geq C_{\bar{z}}$.

To understand the behavior of the seller's payoff with respect to K, we first observe that a dependence of the optimal prices on K only arises when the capacity constraint is binding, i.e., when $Q(p, s, K) = K$. In that case, the shadow value μ of this constraint is nonnegative, so that it cannot be better for a seller to voluntarily announce an available capacity $\hat{K}$ that is strictly less than K. □

Proof of Proposition 2 The first-order necessary optimality conditions for the problem of maximizing the expected social welfare in (20) subject to the constraint $0 \leq Q(p, s) \leq K$ are

$$\bar{V}_Q Q_p + s\bar{z}_p - C_Q Q_p - C_{\bar{z}}\bar{z}_p = (\mu - \nu) Q_s,$$
$$\bar{V}_Q Q_s + \bar{V}_s + \bar{z} + s\bar{z}_s - C_Q Q_s - C_{\bar{z}}\bar{z}_s = (\mu - \nu) Q_p,$$

where μ, ν are the Lagrange multipliers associated with the constraints $Q \leq K$ and $Q \geq 0$, respectively. Using Lemma 2 and Eq. 6 these conditions can be rewritten in the form

$$\phi\bar{\kappa} + \phi(1 - F(\bar{D}))s = \left(C_Q + \mu - \nu\right) + \phi(1 - F(\bar{D}))C_{\bar{z}}, \tag{31}$$
$$\frac{1 - \delta}{1 - F(\bar{D})}\bar{\kappa} + s = \frac{1 - \delta}{\phi(1 - F(\bar{D}))}\left(C_Q + \mu - \nu\right) + C_{\bar{z}}, \tag{32}$$

where $\bar{D} = \bar{D}(Q, s)$ is defined in Eq. 7, and

$$\bar{\kappa} = \int_{\bar{D}}^{\infty} \left(\lambda v_y(\lambda Q, D) - s\right) dF(D) = \left(\lambda E\left[v_y(\lambda Q, \tilde{D}) \middle| \tilde{D} \geq \bar{D}\right] - s\right)\left(1 - F(\bar{D})\right).$$

The unique solution to Eqs. 31 and 32 is given by $s = C_{\bar{z}}$ and $\phi\bar{\kappa} = C_Q + \mu - \nu$, i.e.,

$$\lambda E\left[v_y(\lambda Q, \tilde{D}) \middle| \tilde{D} \geq \bar{D}\right] = \frac{C_Q + \mu - \nu}{\phi(1 - F(\bar{D}))} + C_{\bar{z}}.$$

From Eq. 11 we therefore obtain that $p = \phi\bar{\kappa} = C_Q$, as long as $Q(p, s, K) \in (0, K)$. When, at a given base price p, $Q(p, s, K) = K$ then from Eq. 11 it is possible that $\phi\kappa > p$. In this case the price that society imposes on the buyer is too low compared to the marginal cost, but because of the capacity constraint the allocation remains unaffected as long as p is small enough. In particular, the welfare maximizer can choose the largest possible price p, which equals $\phi\bar{\kappa}$.[26] A similar discussion applies to the other boundary case, where $Q = 0$. We also conclude that it is never optimal for a social-welfare maximizer to artificially constrain the contract volume to a level $\hat{K} < K$ when $K > 0$ is the seller's actual capacity. □

Proof of Proposition 3 The buyer's optimal exercise policy in Eq. 3 and the implicit definition of the strike-price function σ in Eq. 22 imply that

$$\begin{aligned}&\sup\{q \in [0, Q] : \lambda\hat{\phi}v_y(\lambda q, D) \geq \sigma(Q, D, m)\}\\&\quad = \sup\left\{q \in [0, Q] : \lambda\hat{\phi}v_y(\lambda q, D) \geq b(q, D, m)\right\}\end{aligned}$$

for all $Q \in [0, K]$ and all demand realizations D. Since $v_y(Q, D)$ is by the concavity assumption in (2) strictly decreasing, we have that (as long as $0 < z^{\text{FB}}(Q, D, m) < Q$):

$$\sigma(Q, D, m) = \lambda\hat{\phi}v_y(\lambda z^{\text{FB}}(Q, D, m), D) = b(z^{\text{FB}}(Q, D, m), D, m).$$

The first-best second-period allocation is also implemented by the strike-price function $\sigma(Q, D, m)$ if we simply extend the last equality to the cases when $z^{\text{FB}}(Q, D, m)$ is either zero or Q. Using the envelope theorem to differentiate the maximand in (21) we obtain the first-order necessary optimality condition of problem (23) in the form

$$c_Q(Q, z^{\text{FB}}(Q, D, m), D, m) = \kappa^{\text{FB}}(Q, D, m),$$

where

$$\kappa^{\text{FB}}(Q, D, m) = \left[\lambda\hat{\phi}v_y(\lambda Q, \tilde{D}) - c_Q(Q, Q, \tilde{D}, m)\right]_+$$

is the Lagrange multiplier associated with the inequality constraint $z \leq Q$ in (21). Thus, by letting $\bar{\kappa}^{\text{FB}}(Q)$ be the expectation of $\kappa^{\text{FB}}(Q, D, m)$ with respect to the random demand, we can write the solution to (23) in the form

$$Q^{\text{FB}} = \sup\left\{q \in [0, K] : \phi\bar{\kappa}^{\text{FB}}(q) \geq p\right\},$$

in analogy to Eq. 11. We therefore obtain the socially optimal price p as claimed. As in the proof of Proposition 2 it is optimal to set K to the actual available capacity in order to avoid inefficient allocations. □

Proof of Proposition 5 (i) By differentiating the expected social welfare $\bar{W}$ in Eq. 20 with respect to both p and s, and evaluating the result at the ex-ante socially optimal prices (as in Proposition 2), we obtain

$$\bar{W}_{ps} = -C_{Q\bar{z}}Q_sQ_p - (B_Q\bar{z}_s + C_{QQ}Q_s)Q_p \leq 0,$$

[26] Note that the concavity assumption (2) together with Eq. 10 implies that $\partial\bar{\kappa}/\partial Q < 0$.

as a consequence of Lemma 1 and 2 as well as the assumptions on $\hat{c}$ (which are invariant with respect to taking the expectation). In addition, one can show that $\bar{W}_{s\alpha} \leq 0 \leq \bar{W}_{p\alpha}$ at the socially optimal prices. Hence, by implicitly differentiating the first-order necessary optimality conditions with respect to α (cf. Proof of Proposition 2) one obtains that

$$\begin{bmatrix} p'(\alpha) \\ s'(\alpha) \end{bmatrix} = -\frac{\begin{bmatrix} \bar{W}_{ss} & -\bar{W}_{ps} \\ -\bar{W}_{ps} & \bar{W}_{pp} \end{bmatrix} \begin{bmatrix} \bar{W}_{p\alpha} \\ \bar{W}_{s\alpha} \end{bmatrix}}{\bar{W}_{pp}\bar{W}_{ss} - \bar{W}_{p\alpha}^2} \geq 0.$$

(ii) The proof of this part proceeds analogously to the proof of part (i) and is therefore omitted. □

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