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Abstract

In California, the tremendous spatial and temporal variation in precipitation suggests that flexible contractual arrangements, such as option contracts, would increase allocative efficiency of water. Under such arrangements, a water agency pays an option premium for the right to purchase water at some point in the future, if water conditions turn out to be dry. The premium represents the value of the flexibility gained by the buyer from postponing its decision whether to purchase water. In California, the seller of existing option arrangements is often an agricultural producer who can fallow land in the event that a water option is exercised.

We seek to determine the value of transferring water supply risk from one party to another at key locations in California, given current water prices and the spatial and temporal distribution of water year types in the state. We utilize output from CALVIN, an economic-engineering optimization model of the California water system, to construct a mathematical programming model that runs historical hydrological conditions over the current configuration of the California water system.

Our model allocates water between current-year agricultural and urban demand and future anticipated excess demand without knowledge of future water conditions. This limited foresight and the consequent storage levels results in a distribution of water's imputed price at different locations throughout northern California. We utilize these distributions of water price to calculate annual option premia at key locations in California. Analysis performed to date covers northern California.

Introduction and Problem Statement

As water value increases, institutional mechanisms evolve to reflect increased scarcity of water. One such institutional mechanism is water markets, which have significantly improved the allocation of water. (See, for example, Hearne and Easter (1987) and Howitt (1994), who have calculated gains from trade associated with water market implementation in Chile and California, respectively.) In California, the tremendous spatial and temporal variation in precipitation suggests that flexible arrangements for trading water, such as option contracts, would even further increase allocative efficiency of water. Under such arrangements, a water agency pays an option premium for the right to purchase water at some point in the future, if water conditions turn out to be dry. The premium represents the value of the flexibility gained by the buyer from postponing its decision whether to purchase water. In California, the seller of existing option arrangements is often an agricultural producer who can fallow land, in the event that the water option is exercised.

Although the variation in precipitation suggests that option agreements would benefit water users, water options trading in California has been limited. A well-functioning options market in California would help make better use of existing storage, provide an alternative to additional storage construction, and reduce the supply risk inherent in the California water system. In this analysis we seek to determine the likely value of transferring water supply risk from one party to another at several locations in California, using current water prices and the spatial and temporal distribution of water year types in the state.

Option agreements allow water agencies to manage water supply risk. In the fall of 1994, after several years of drought conditions, the California Department of Water Resources implemented an options bank (Jercich, 1997). Option contracts purchased from willing sellers through the bank allowed wholesale water purchasers to manage their supply risk in the event that 1995 was as dry as the previous year had been. After the option contracts were signed, late season rainfall and snow-pack changed the water year from dry to wet. Consequently, no water agency that had bought an option exercised its purchase rights. However, the willingness of water agencies to purchase options through the bank demonstrated that options can be a cost-effective way for water agencies to prepare for potential drought. More recently, several water agencies, most notably Metropolitan Water District of Southern California (MWD), have implemented long-term bilateral option agreements. Option agreements may also act as a substitute for use of more expensive methods of meeting existing contractual obligations. For example, the Bureau of Reclamation is exploring the use of forbearance agreements with its water contractors on the Lower Colorado River, as a relatively cost-effective way to meet its treaty obligations with Mexico in dry years (Kleinman, 2006).

The benefits of implementing dry-year contingency markets have been calculated in other parts of the western United States. Hamilton, Whittlesey and Halverson (1989) determined that forming interruptible power markets, so that agricultural users in the Pacific Northwest could leave water in the river for hydroelectric generation during dry years, would increase the value of water nine times over. Clark and Abt (1993) also found through simulation that implementing water options in northern Colorado would be less expensive than water rights purchases or new infrastructure investment. Michelsen and Young (1993) came to the same conclusion, noting that option contracts on irrigation water rights in Colorado are a relatively inexpensive form of drought insurance for urban water agencies.

Watters (1995) calculated the efficient option prices predicted by the binomial and Black-Scholes option pricing models for three bilateral contracts in southern California and determined that the contracts were sensibly priced. As Watters only had access to historical prices of water transactions in California, she was unable to use her results to determine whether a much more active options market would benefit California, as we are able to do. More recently, Villinski (2003) used a finite-horizon, discrete-time, stochastic dynamic programming methodology for valuing multiple-exercise option contracts in the Texas Lower Rio Grande. Our analysis will have the benefit of a longer data series (72 years of monthly simulated data rather than 18 months of actual data) and option price predictions across all sectors of the economy (rather than trades solely between irrigators).

Objectives

The specific objectives of our research program were to:

1. Construct a simulation-optimization model of the California water system patterned after CALVIN, an economic-engineering optimization model of the California water system, yet more realistically constrained by limited foresight;
2. Generate with this model a distribution of water's imputed value at key locations in California; and
3. Evaluate theoretical, location-specific option value using these distributions of water's imputed value and tools from finance theory to determine whether, given the state's existing water system and hydrology, intra-year or inter-year options would generate greater gains from trade in California.

Procedures

Like Watters (1995), we follow Cox, Ross, and Rubinstein (1979), who derive a binomial option pricing model which approximates the Black-Scholes option price model in the limit. However, rather than use existing bilateral option agreements in California, of which there are not many, we use a simulation-optimization model to generate a distribution of water prices from which to calculate option prices. To price a call option for California water, we need the underlying water price, the variance of the rate of return on water, the exercise price of the option, the time to maturity of the option, and the risk-free interest rate. The simulation-optimization model provides a vector of water prices from which to make a theoretical calculation of option value.

The starting point of our analysis is CALVIN, an economic-engineering optimization model of the California water system developed at University of California, Davis (Draper, et al., 2003). The generalized network flow optimization framework of CALVIN allocates water to agricultural and urban users so as to minimize economic losses, subject to flow and balance constraints on the network. CALVIN runs the current configuration of the California water system and estimation of current economic demand functions through 72 years of historical hydrological conditions. CALVIN is the first engineering model of the California water system to utilize economic demand functions to allocate water among users.

However, CALVIN makes storage, flow and use decisions with perfect foresight of the entire 72-year hydrological cycle. Thus, the resulting storage patterns are only optimal in the presence of full knowledge of future water conditions. Our model addresses this shortcoming by optimizing annual allocations of the current California water system on an annual time step over historical hydrological conditions, so that allocation occurs with limited foresight. This model maximizes agricultural and urban surplus subject to water transport costs and a constraint on the carryover value of water from one year to the next. The challenge is to infer from observed behavior for known water year conditions how allocation on the network will occur over a variety of water years, when future water supply is uncertain. We use self-calibration. The methodology, as described in Howitt (1995), Howitt (1998), and Cai and Wang (2006), is as follows.

The model allocates flows over the network, using observed deliveries and inflows, to generate the economic values which underlie the observed decisions. We use several years for this initial calibration stage, in order to capture behavior over a variety of water year types. In this analysis, observed behavior is from a base run of the CALVIN model. These values are used to generate a calibrated cost function, which is unconstrained yet still reflects the values which underlie the observed decisions. This cost function, or forcing function, represents factors that affect behavior but that have not been specifically quantified in the underlying engineering model. Such factors may include risk, cost and benefit function nonlinearities, and operating constraints.

Finally, the model uses this unconstrained, calibrated cost function to run existing demands through a longer series of water years. The resulting limited foresight model generates shadow values that indicate water's true economic value at the storage reservoirs and demand centers each of the 72 years of the hydrological history. The model currently uses hydrological conditions from 1922 to 1993. An option's value is the difference between the option's exercise price and the probability-weighted higher price that would have been paid in the absence of the option.

Figure 1 indicates the full geographic extent of the model. In the north (to the left) are Whiskeytown and Shasta Lakes. The model extends south (to the right) through nine agricultural demand regions to the Tracy Pumping Plant and the Harvey O. Banks Pumping Plant in the Sacramento-San Joaquin Delta. These two pumping plants are at the entrance to the 444-mile California Aqueduct, the central artery of the State Water Project in the Sacramento-San Joaquin Delta. Option value at these locations will indicate the value of an annual option to the water agencies likely to be acquiring water options farther south in California.

Thus far, the model extends from the three northernmost reservoirs in California (Lake Shasta, Whiskeytown Lake, Clair Engle Lake) to the floor of the Sacramento Valley. In addition to the three surface water reservoirs, the model includes a groundwater reservoir and agricultural and urban demand nodes. Figure 2 is a schematic of this northernmost region of the model.

Results

In the current configuration of the model, there are two network nodes across which the economic value of flows is measured. The first node, C3, is directly adjacent to the agricultural demand center of the region. The second node, C5, is the southernmost node in the current configuration of the model, which connects to the remainder of the California water system.

The shadow prices reported at these nodes indicate the economic value associated with one additional unit of water flowing across these points. At the first node, C3, there is no economic value associated with moving additional water across this node. Given the functions of agricultural and urban demand currently utilized in the model, the marginal value of water is effectively zero. At the second node, C5, there is considerable economic value associated with additional flows. This result is unsurprising, given the strong demand for water downstream from C5, in the south of California.

Figure 3 graphs the distribution of prices generated by our simulation model against the distribution of the underlying stochastic phenomenon, precipitation on the Sacramento River over the 72-year hydrological history. The negative correlation between amount of precipitation and the prices at the southern California node indicates that low precipitation corresponds to high water value within our model, as expected. The distribution of water prices is clearly skewed; prices are relatively higher in dry years than they are low in wet years. These positive spikes in price unaccompanied by corresponding negative spikes in price are evidence that water options at this node will have positive value. They are a result of the model's carryover storage value function signaling the value of storing water for future use.

The first column of Table 1 indicates the value of an annual option at each of the C3 and C5 nodes when the exercise price associated with the option is set equal to the average expected price at the node. Increasing exercise price above the average water price decreases the value of the option accordingly. Figure 4 illustrates the inverse relationship between an option's exercise price and its value. On the vertical axis is the value of an option at the start of the water year, for exercise one year in the future. On the horizontal axis is the strike price, measured as a percentage above the average annual price for the node. As the strike price increases, the value of the option decreases. For a given strike price, option value at the higher-value C5 is higher than at C3.

Table 2 compares our results to date with existing option agreements, namely, the DWR drought options bank of the 1990s and the option agreement between MWD and Sacramento Valley water agencies. For both the DWR options bank and the MWD bilateral contract, the exercise price is approximately 20% above the average water price. Options at C3 and C5 with comparable terms are consequently chosen for comparison. Option value is much lower for the nodes in our model than for the real-life option deals, both in absolute terms and as a percentage of water price and exercise price.

Our model's option values are low relative to observed option values in the third and fourth columns. Extension of the model further south to the Delta and incorporation of urban demand along the way will increase our model's estimation of option value. The option values generated by the model at the southernmost tip of the model at the Delta (at the Harvey Banks pump and the Tracy pump) will be most interesting and provide values that are most interesting for comparison to existing bilateral option agreements in California.

Conclusion

Simulated flows and deliveries from CALVIN, historical hydrological data, and data on current agricultural and urban demands allow us to generate the location-specific value of annual water options in California. While the existing simplified model makes clear the principle of calculating water value using these simulation methods, we are ultimately interested in using these methods to provide policymakers in California with an indication of the locational and seasonal value of water options. Thus, work continues on expanding the model south to the Sacramento-San Joaquin Delta.

Previous theoretical calculations of option value in the western United States have far exceeded option premia on existing bilateral contracts. Actual option value will be lower than the theoretical calculation in the presence of other mechanisms for allocating water efficiently over time, such as storage, groundwater substitution, and spot and exchange contracts. However, avoidable transaction costs may also explain why past calculations of gains from trade associated with option markets have been significantly higher than option valuations negotiated in existing contracts.

Our original research question regarding the ability of annual water options to increase market efficiency has led to additional research projects with hydrologists at University of California, Davis, and economists at California State University, Sacramento and the Bureau of Reclamation, Lower Colorado Region.

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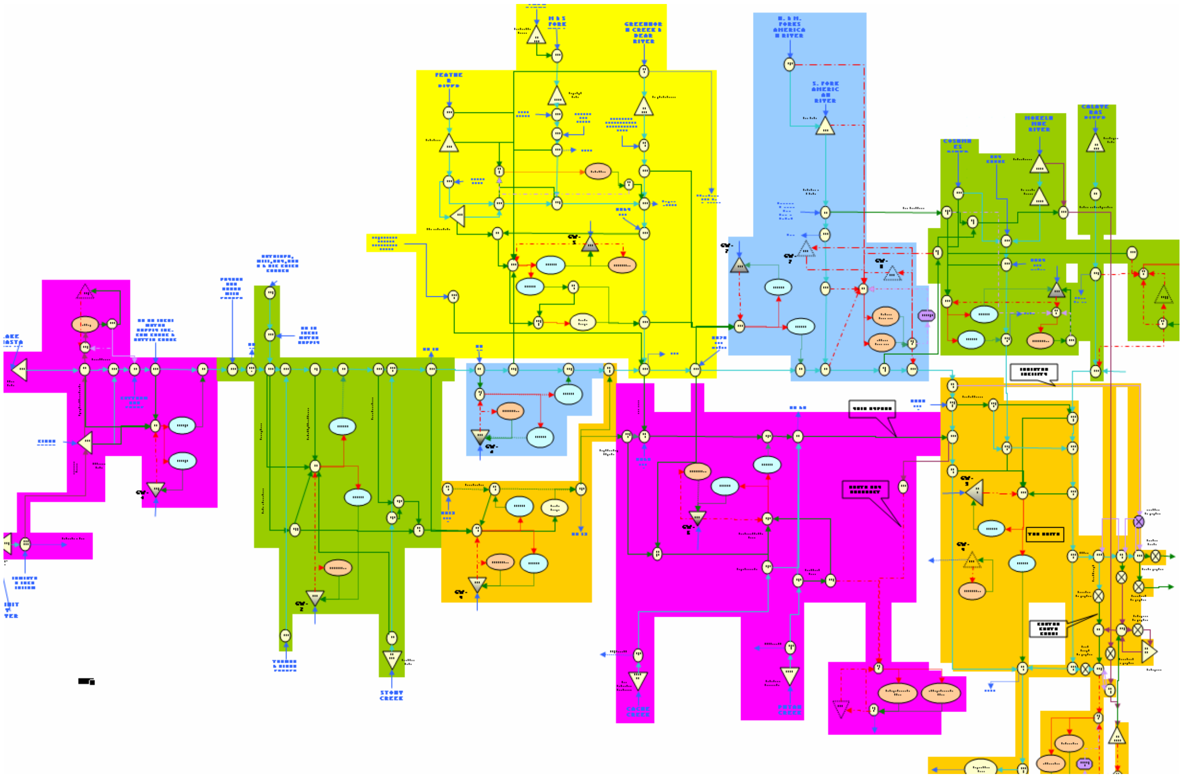

Figure 1: Northern California's Water Infrastructure. Adapted from Economic-Engineering Optimization of California's Future Water Supply: CALVIN model schematic, September 2001.

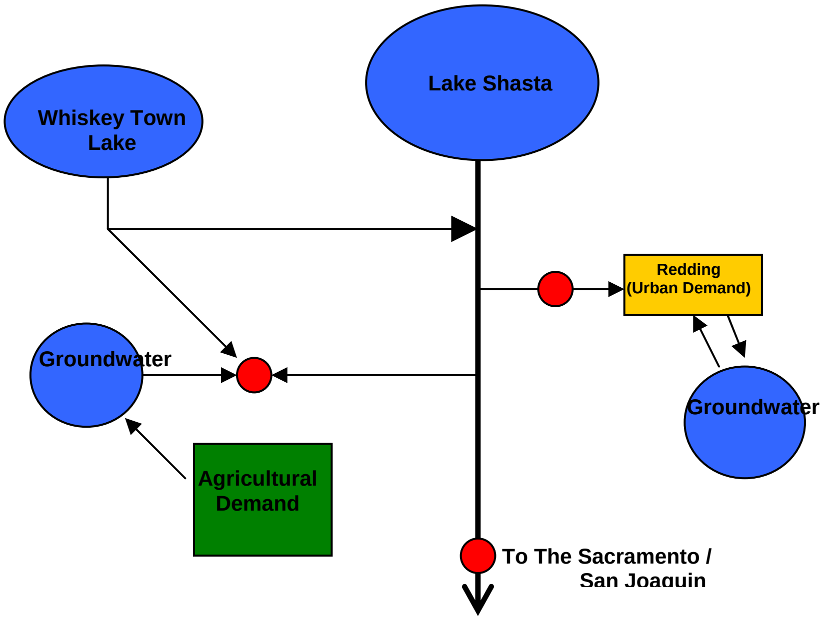

Figure 2. Stylistic Schematic of the Model’s Northernmost Region.

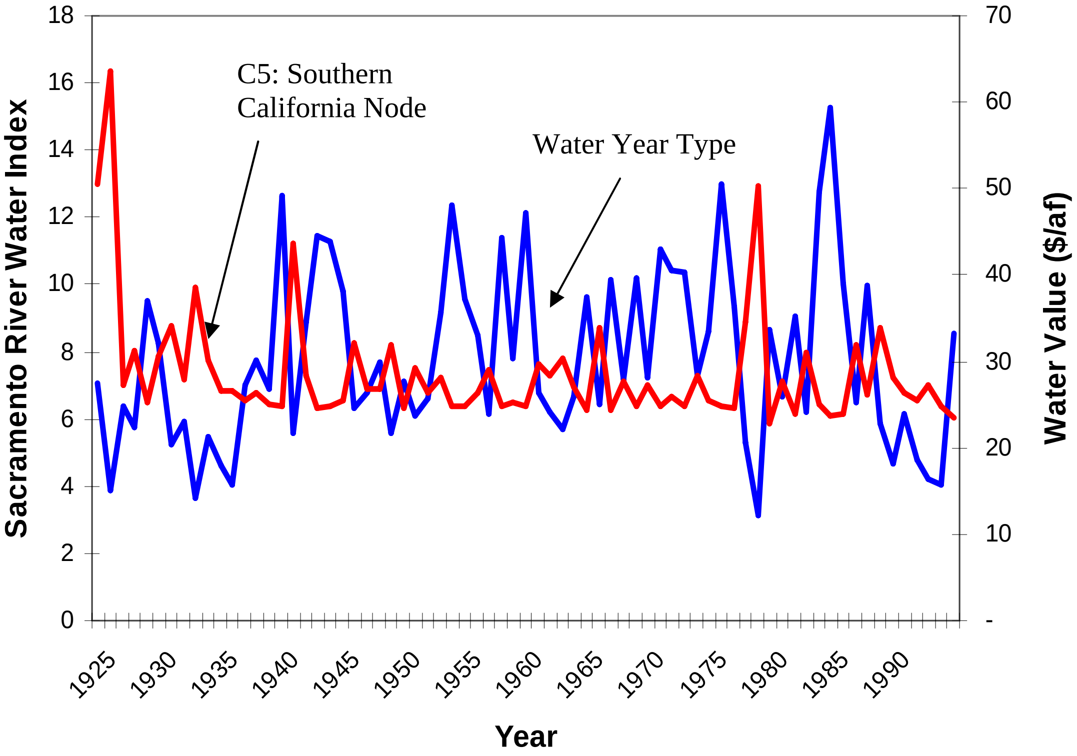

Figure 3. Water Year Type and Southern California Node Price Over Time.

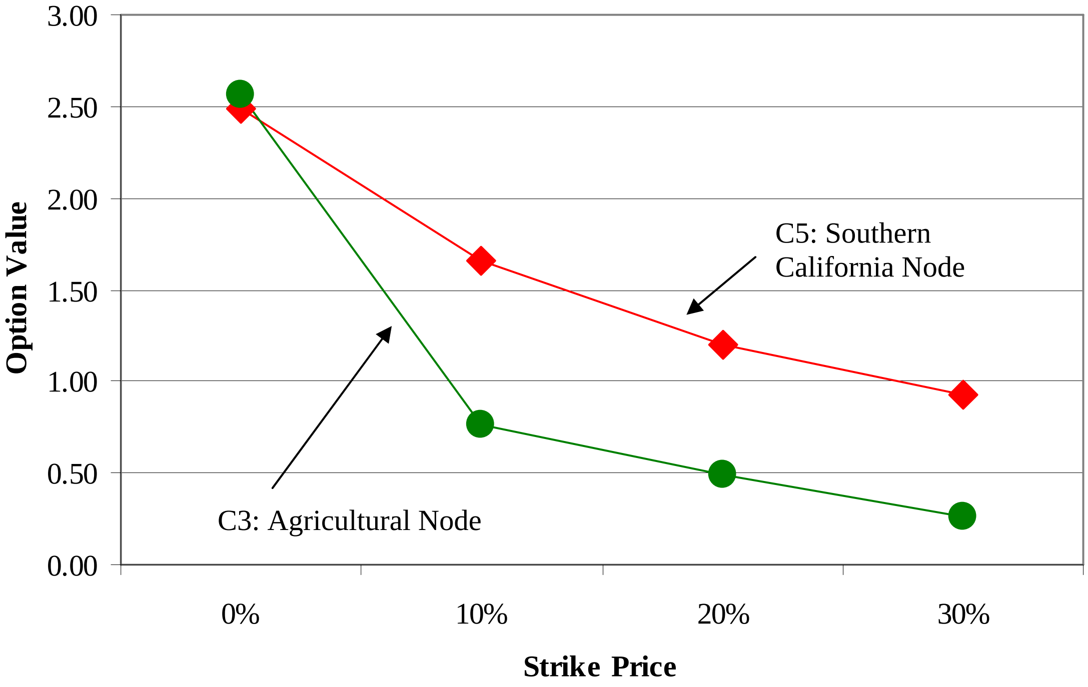

Figure 4. Option Value as a Function of Strike Price (Percentage Above Average Water Value).

Table 1. Option Value as a Function of Strike Price					
		Exercise Price Equals:			
		Avge Water Price	**Avge Water Price + 10%**	**Avge Water Price + 20%**	**Avge Water Price + 30%**
C5: Southern California Node	**Exercise Price**	28.64	31.51	34.37	37.23
	Option Price	2.49	1.66	1.20	0.93
C3: Agricultural Node	**Exercise Price**	22.23	24.46	26.68	28.90
	Option Price	2.56	0.76	0.49	0.26

Table 2. Comparison of Results to Existing Option Agreements				
	C5: Southern CA Node	**C3: Agriculture Node**	**DWR Option Bank**	**MWD Bilateral Contract**
Water Price	29	22	31	92
Exercise Price	31	25	38	110
Option Premium	1.7	0.8	3.5	10.0
Option as % of Water Price	5.9%	3.6%	11.2%	10.9%
Option as % of Exercise Price	5.5%	3.2%	9.3%	9.1%