The Design of "Smart" Water Market Institutions Using Laboratory Experiments

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The Design of "Smart" Water Market Institutions Using Laboratory Experiments [*]

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1. Abstract

One of the problems with proposals for substantial institutional change in water systems is that modification and irreversibility make the process slow, cautious and costly to society. In this paper, we discuss the role that experimental economics can play in evaluating proposed institutional changes to help facilitate a more rapid and smooth adoption of changes in the water system. Experimental economics yields a formal and replicable system for analyzing alternative market structures before they are actually implemented. For example, a water market can be developed and tested in the laboratory under supply and demand constraints that reflect drought conditions that might occur in California, or other arid regions in the world. We present a prototype of a California water transfer model and the results from a series of water market experiments. Results include realized market efficiency and surplus distribution, as well as an analysis of market price volatility. The implications of this research extend well beyond California water markets, not only to water markets in other arid regions, but also to the design of markets for other environmental goods, including tradable pollution permits and fishery ITQs.

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2. Introduction

Many of the large, complex water systems throughout the world depend upon a centralized authority both to solve the fundamental coordination problems and to dictate solutions to allocation issues. These problems are often exacerbated by factors such as the public good nature of water, externalities associated with transporting and consuming water, and the economies of scale in shared production facilities. In our world of rapid technological and environmental change, these centrally managed systems tend to react too slowly to allow society to adapt efficiently. One of the problems with proposals for substantial institutional change is that adaptation and irreversibility make the process slow, cautious and costly to society. In this paper, we discuss both the recent development of computer-assisted markets, which provide the promise of developing decentralized solutions to these complex resource allocation problems, and the role that experimental economics can play in evaluating proposed institutional changes. We present the results of an application of this experimental approach to water markets in California, and then discuss the applicability of this methodology for the design and testing of water markets in other regions.

The water market institution we discuss in this paper is based on the so-called ‘smart’ market concept developed by McCabe*, et al.* 1989; 1991; 1993 which allows for the pricing and allocation of resources in technologically interdependent environments. The essential idea is to combine the information and incentive advantages of decentralized ownership rights or responsibilities with the coordination advantages of central processing. The optimization data requirements for these computer-coordinated markets come in the form of willingness-to-pay (WTP) demand, willingness-to-accept (WTA) supply, and budget and capacity constraints, that are provided by decentralized decision-makers whenever price and allocation decisions are required. The required input data are available only from dispersed human decision-makers who best know their own circumstances and willingness to exchange. The central program applies optimization algorithms to the submitted bid-offer messages to determine the prices and allocations that maximize the gains from exchange.

This paper presents the results of a series of experiments designed to test the viability of computer-coordinated water markets. The next section reviews experimental economics and its application to water markets. This is followed by a discussion of the experimental design and the derivation of the supply and demand functions. The paper wraps up with a presentation of the results and some concluding remarks.

3. Designing a Market for Water

In California, annual precipitation is characterized by extremes, and multi-year droughts are a relatively common phenomenon. Most of the primary agricultural and urban centers are located in arid parts of the state and rely on water imported from other regions to meet the demands of irrigated agriculture, municipal and industrial uses. Environmental demands for water to protect fish and wildlife have reduced the supply of water available for consumptive use in the agricultural and urban sectors, yet the demand for water continues to increase due to population growth. Despite substantial investment in a complex water supply infrastructure, it appears that the current system may be inadequate for meeting the state’s forecasted water demands into the next century. Since large public investments in building new dams and irrigation projects are unlikely, California will have to develop new strategies for meeting future demands. Although this paper focuses specifically on California, this situation parallels that of many other regions throughout the world, including the Western United States and many arid nations.

Economists have long advocated the use of water markets to help mitigate these disparities between water availability and demand. Easter, *et al.* 1998, as well as countless others, provide evidence indicating that the development of markets can improve water allocation by permitting the compensated, voluntary transfer of water to its highest-valued use. However, the allocation of private property rights can be successful only if there is an efficient mechanism to allocate and trade the rights. Although the advantages of water markets are well-prescribed, economic theory says little about how different market institutions can affect allocations. Experimental research clearly indicates that the rules governing trading play a vital role in determining the market outcomes and the realized gains from trade (Smith 1982; Kagel 1995). For example, it is well known that posted-offer and continuous double auctions display dramatic differences in capacity to track changing market conditions.

With the advent of high-speed communication networks and low-cost computing resources, the landscape of exchange system architectures has changed dramatically over the past decade. Smart computer-coordinated markets have recently come to the fore. These markets allow decentralized agents, who best know their own circumstances, to submit virtually unlimited messages (bids to buy, offers to sell, logical and budgetary constraints) to a computer dispatch center. The center can then compute prices and allocations by applying a set of rules, often a sophisticated optimization algorithm that maximizes the possible gains from exchange, while observing constraints.

Considering that substantial institutional change is often slow and costly to society, using experimental economics to analyze alternative market structures before they are actually implemented can offer significant benefits. Once implemented, modifying a new institution will be difficult, making it essential that reforms are initially enacted correctly. A poorly designed institution could have undesirable consequences, possibly eroding the potential benefits and exacerbating the problem that the change was originally intended to resolve, and negating the opportunity for further innovation. Laboratory experiments are a formal, replicable, and relatively inexpensive means of analyzing different market mechanisms. Properly designed experiments can be used to test the robustness of these institutions across a wide array of environmental conditions, provide insights into the incentive properties of the institutions, and highlight potential problem areas, thereby helping to avoid costly design errors.

In the following sections, we discuss the role that experimental economics can play in evaluating proposed institutional changes to help facilitate a more rapid and smooth adoption of changes in the water system, and test these institutions using laboratory experiments based on California conditions. A successful water market institution in California will have to address complex allocation problems that arise from myriad factors such as environmental and third-party impacts, conveyance and storage constraints, groundwater impacts, and high transaction costs. In this research program we develop and test a ‘smart,’ computer-assisted market mechanism that is designed to provide decentralized solutions to the fundamental coordination problems that the state faces. Conducting experiments that model the conditions prevailing in California allows us to collect real and valuable data that does not exist elsewhere. Having developed the generic approach, the application to conditions in other regions is straightforward.

4. Experimental Design

This series of laboratory experiments was designed to study the efficiency and price performance characteristics of the sealed-bid uniform price double auction (UPDA) mechanism for the simultaneous allocation of water and transportation capacity rights among buyers, sellers, and transporters. As an auction mechanism with continuous feedback and opportunities to improve bids and offers, UPDA's distinguishing feature is that all accepted bids to buy are ultimately filled at a price less than or equal to the lowest accepted bid price of buyers – a price that just clears the market by making the total number of units sold equal to the number purchased. Similarly, all accepted offers to sell water are filled at a price greater than or equal to the highest accepted asking price of sellers. This contrasts with the discriminative continuous double auction in which different buyers may pay different prices for the same commodity, and sellers might receive different prices for identical goods.

This computer-coordinated auction market maximizes total gains from exchange based on the submitted bids and offers, and determines allocations and nondiscriminatory prices at all nodes. Some of the salient features of this spot water market are as follows:

(1) Consumption centers, consisting of wholesale water buyers such as agricultural water districts and urban water agencies, are connected to water sources by a capacity-constrained transportation network. At this initial stage, the network we study is relatively "thin," and weakly competitive. In this sense, it is intended as a worst-case scenario for any price mechanism.

(2) The auction market uses computer support to process location-specific bid schedules from water buyers, location-specific offer schedules from water right holders, and segment-specific offer schedules of transfer capacity from transportation right holders. This means that each of the three types of participants are required to make judgments that reflect their own private circumstances, *i.e.*, their willingness to buy, sell or transport water at their respective location in the network.

(3) The resulting prices in the market are nondiscriminatory, *i.e.*, all sellers at the same location receive the same price, all buyers at the same location pay the same price, and all transport links connecting two nodes obtain the same price. In a given trading period, differences in the price of water between any two locations reflect differences in the marginal supply price of transportation and/or link capacity restrictions.

(4) The allocation of delivered water among buyers, of injected water among sellers, and of the resulting transportation requirements maximizes the total gains from exchange given the *submitted* schedules of buyer bids, seller offers and transportation offers.

We report the results of 13 experiments that were divided into two treatments: (1) Southern California conveyance links were controlled by a single subject (six experiments, yielding 134 market observations), and (2) cotenant rights to Southern California transportation capacity (seven experiments, yielding 136 market observations). These two treatments are discussed in more detail later. Subjects were recruited from the undergraduate student population at the University of Arizona.

Instructions were presented to the participants via a 30 minute oral presentation that included overheads with images from the various screens. Initially, the subjects were all trained in a perfectly symmetric six node circular environment (three buy nodes interspersed with three sell nodes) in which they each owned identical rights to buy, sell and transport water. Students were permitted to ask questions during the training period. The data from these training experiments were disregarded. After the training sessions, the subjects were recruited to participate in a two-day experiment, with preference given to those students who earned the most money during the trainer. Students who performed poorly were not invited to return. At the end of the second day, the subjects were paid their total profit earnings in the experiments in addition to a $10 show-up payment. The cumulative profits over the two days ranged from $10 to $70 per subject, not including the show-up payment.

Each experiment consisted of a single six minute practice period, followed by a series of four minute trading periods. The actual number of periods in each experiment varied between 7 and 24.[1] Subjects were not told when the experiment would terminate. All the experiments were run in the Economic Science Laboratory at the University of Arizona using a Windows-based application designed specifically for these water market experiments. This software (1) enforces the bidding rules that define the UPDA institution, (2) continuously calculates the tentative optimal resource allocations, (3) displays the water network along with the tentative market price and quantity at each node, (4) informs subjects about which of their bids (or asks) were tentatively accepted at each node and computes profits, and (5) provides market history data reporting the results of prior trading periods.

During each four-minute trading period, subjects can submit location-specific bids and asks as frequently as they wish, subject to an improvement rule which required that each new bid to buy water must be at a higher price or increased quantity than the previous submission, and each new offer to sell or transport water must be at a lower price or increased quantity. These submissions could be divided into as many as five separate price-quantity steps. After each new submission, the computer instantaneously recalculates the allocations and reports the new

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[1] The original plan was for all experiments to be 24 periods. However, technical problems delayed the start of some experiments, limiting the number of periods.

equilibrium prices and quantities for each node. These allocations are tentative until the market is called after four minutes, at which time they become binding contracts, profits are computed, and a new period begins.

For any set of submitted bids and offers, the total realized surplus in the network is maximized by solving the following linear programming problem:

(1) Maximize total surplus: $-\sum_{i} c_i f_i$

subject to:

(2) balance of flow: $\sum_{i \in S_k} f_k = \sum_{i \in E_j} f_j$ ($\forall$ nodes j);

(3) conveyance capacity: $d_i \le f_i \le u_i$ ($\forall$ arcs i).

Each arc (i) in this formulation represents one bid or offer. If a buyer makes a two-part bid, then it is represented by two parallel arcs. Two-part offers by sellers are represented similarly. Thus, each bid or offer is represented by the vector $(s_i, e_i, d_i, u_i, c_i)$ with s_i being its starting node, e_i its end node, d_i the least permissible flow on that arc, u_i the greatest permissible flow on that arc (determined by the bid or offer quantity entered), and c_i the bid value or offer price per unit of flow on that arc (bid values are negative costs). The flow on arc i is f_i, S_j is the set of arcs which begin at node j, and E_j is the set of arcs which end at node j. Note that constraint set (2) maintains the balance of flow at each node j. Intuitively, equation (2) describes the network and defines the set of feasible trades. Constraint set (3) ensures that the flow on each conveyance arc does not exceed the stated lower or upper bounds.

Solving the linear programming problem (1)-(3) yields not only the optimal flows (and production and consumption patterns), but also the set of shadow prices, l_j, for all nodes in the network. Since the shadow prices are marginal nodal values at which water is bought and sold, the difference in shadow prices at the start and end nodes of an arc gives us the value of the marginal unit of flow on that arc, *i.e.*, the price associated with water conveyance.

This market was designed as a simplified wholesale spot water market in California, similar in purpose to the state drought water banks in 1991, 1992, and 1994. The key components of this network that characterize the situation in California are: (1) consumption of water in irrigated agriculture and at urban centers, (2) surface and groundwater supplies, (3) prohibition on the transfer of groundwater, (4) Delta export restrictions due to environmental constraints, (5) pumping and conveyance costs for water delivery. In this market, there were three types of activities: buying, selling, and transporting water. There were nine subjects active at a total of 17 nodes (shown in Figure 1), and most subjects were able to engage in more than one activity. Each participant was assigned a subject identification number, ranging from one to nine. Each of these nine subject numbers corresponded to a particular set of rights, and the rights for each subject number were identical in each experiment – with the exception of the different canal ownership structures in the cotenancy/no-cotenancy experiments. The allocation of these rights is shown in Figure 1. There were three sources of surface water (the Sacramento, San Joaquin and Colorado Rivers), three sources of groundwater, five urban buyers, four agricultural water districts, and two conveyance links with active agents. Flows from the Sacramento and San Joaquin Rivers converged at the Delta, where there was a constraint on export pumping capacity to Southern California. Water also flowed into Southern California from the Colorado River via the Colorado River Aqueduct which is currently owned and operated by Metropolitan Water District (MWD).[2]

{INSERT FIGURE 1}

The four agricultural agents represented the Sacramento Valley, Northern San Joaquin Valley, Southern San Joaquin Valley, and Colorado River irrigators. Each of these agents had rights to sell water from a reservoir into the network and to purchase water at their respective locations. In addition, the first three agricultural agents also had access to local groundwater supplies. This groundwater could be substituted for surface flows, but could not be exported from the region. There were no pumping externalities since there was only a single agent drawing from each aquifer.

The five urban water agencies were Sacramento, the San Francisco Bay Area, the San Joaquin Valley cities, Metropolitan Water District (Los Angeles), and San Diego. Unlike their agricultural counterparts, the urban agencies did not have any water rights in this network because the urban demand schedules were for *transferred* water, not total water demand. We assumed that urban water agencies will be interested in acquiring, not selling, water on a regular basis because (1) the urban sector only controls about 20 percent of the state's developed surface water supplies, (2) given this initial allocation, the marginal value of water in urban use exceeds the opportunity cost of conserving water in agriculture (including conveyance costs), and (3) the urban demand for water is increasing due to population growth.

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[2] Metropolitan Water District of Southern California is the largest municipal water district in the state. The district is the water wholesaler for 27 local water agencies and 210 subagencies, with a total annual demand exceeding 3.5 million acre-feet (Lund and Israel, 1992).

Transporting water through the three rivers was costless and unconstrained. There were four nodes at which conveyance costs existed: (1) the Delta pumps, (2) the federal- and state-owned canals south of the Delta, (3) the Colorado River Aqueduct, and (4) the San Diego Aqueduct. The first two were operated by a "robot" that simply revealed the true marginal cost at these nodes and did not engage in any strategic behavior. However, the export limits at the pumps typically generated congestion rents that reflected the shadow value of the constraint: the amount the market price of imported water exceeds the marginal supply cost. The latter two conveyance facilities were controlled by at least one active subject, depending upon the environment. The precise nature of the ownership arrangements is discussed in more detail below.

The supply and demand schedules used by the experimental subjects are derived from an empirical water transfer model that combines an agricultural production model with urban demand functions.[3] Because there have been relatively few water transfers in California, and reliable data on those transfers are difficult to obtain, it is not possible to estimate a meaningful demand schedule based on past transfers, particularly at the regional level. Hence, we derive the demand parameters from a non-linear programming model of agricultural production in California. From this, we can estimate the demand for water in each region.

The agricultural production model is based on the Central Valley Production and Transfer Model (CVPTM) described in U.S. Department of the Interior (1997). The CVPTM was initially developed in 1994 as part of the Programmatic Environmental Impact Statement which modeled the effects of certain provisions of the Central Valley Project Improvement Act (CVPIA) on

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[3] The parameters used in the experiments are available from the authors upon request.

irrigated agriculture. The CVPTM uses an elasticity calibration approach, which combines econometrically estimated elasticities with positive mathematical programming (PMP) techniques to develop a regional agricultural production and economic model that simulates the decisions of agricultural producers in California's Central Valley. Briefly, PMP models differ from standard linear production models by using nonlinear cost functions that are implicit in the observed land allocations. PMP models calibrate to the base data extremely well, without using overly restrictive constraints that are common in many other models. These models are generally quite robust, and therefore are quite useful for policy simulations (Howitt 1995a; 1995b).

The CVPTM assumes that farmers maximize profits in a competitive market, subject to resource, technical, and market constraints. To define the competitive equilibrium, the model maximizes the sum of producer and consumer surplus. The model includes 22 agricultural regions and 26 categories of crops, which we have aggregated into three regions (the Sacramento Valley and two San Joaquin Valley regions) and 12 crops. The model includes CES isoquants to reflect the trade-off that farmers face between water use and investments in irrigation technology. By changing the supply of water available in a particular agricultural region and computing its shadow price, we are able to obtain a set of price-quantity observations that we then used to estimate a log-linear regional water demand function. The CVPTM also includes water transfer demand functions for 10 major groups of urban water agencies that we aggregated into five regions. These demand functions are based on water shortage estimates, capacity limitations, costs of alternative supplies, and costs of shortages.

The model includes four sources of water for each region: the Central Valley Project (CVP), the State Water Project (SWP), local surface water, and local groundwater. Each region was forced to purchase, but not necessarily consume, their CVP and SWP allocations. This was done by converting the per acre-foot contract price of these water supplies into an unavoidable fixed cost, and setting the variable cost to zero. Not surprisingly, this fixed cost had little impact on market behavior, largely because the difference between the market price and the subsidized cost was so great that recovering the fixed costs was trivial.

In California, the primary source of water supply uncertainty is not *when* or *where* the precipitation will occur during a given water year, but rather *how much*. Statewide annual run-off is characterized by the extremes of droughts and floods. In these market experiments, subjects faced a fluctuating supply of water; demand was held constant. The supply of water varied in a predictable pattern that was announced to the subjects at the start of the experiment. The supply was made deterministic because we assume that this spot market operates after the rainy season has concluded and the supply for that particular water year is known with a high degree of certainty.

In the experiments, the water supply followed an eight period cycle: three “high” supply periods, one “medium” supply period, three “low” supply periods, one “medium” supply period, then repeat. In the high supply periods, sellers had 100 percent of their base surface water allocations, in the medium periods they had 80 percent, and in the low periods 60 percent. The reduction in surface water supplies was mitigated somewhat by permitting additional groundwater pumping. Specifically, each region was given additional groundwater supplies equal to 80 percent of their surface water supply decrease, but this groundwater could not be exported.

We also evaluated the implications of alternative property right structures for conveyance capacity, specifically the use of competitive cotenancy rules to introduce competition where only a single pipeline facility is needed. In such “natural monopoly” situations, competitive policy requires the capacity of such facilities to be shared by multiple owners (which is commonly the case for many large investments). The individual rights holders then submit separate offer schedules for their share of the capacity. This yields competitive outcomes in the short-run since the ownership structure is as if there existed parallel distinct pipelines with capacities equal to that of each shareholder. To get the long-run competitive outcome one needs a property right rule stating that any cotenant or independent outsider is free to invest in augmenting the capacity of the pipeline in return for the right to the increase in capacity. The point is that unique facilities need not imply a natural monopoly as long as there are property right rules defining multiple rights holders who then must compete by using these rights to supply consumers with commodity or services. (See Rassenti *et al.* 1994, for a discussion of cotenancy property right rules and an experimental evaluation of its efficacy for inducing competition on bottleneck pipelines).

This issue of monopoly control over conveyance capacity is particularly relevant in light of the recent litigation in Southern California over the transportation of Colorado River water to San Diego. In order for holders of Colorado water rights, such as the Imperial Valley growers, to sell some of their water to the city of San Diego, the water must pass through the Colorado River Aqueduct, which is controlled by Metropolitan Water District. Although state law requires that excess conveyance capacity be made available at marginal cost, there is considerable debate regarding what can be included in this cost.

In our experimental network, there were two conveyance links that were controlled by active subjects: the Colorado River Aqueduct (node L3 in Figure 1), and the San Diego Aqueduct (node L4). In the “no cotenancy” experiments, both of these lines were under the exclusive control of Metropolitan Water District. Under “cotenancy,” Metropolitan Water

District, Colorado River Agriculture, and San Diego each controlled one-third of the capacity. Variable conveyance costs were identical for each agent.

5. RESULTS

There are three measures of market performance that we discuss in this section: efficiency, distribution of surplus, and volatility. After defining the terms, we use these criteria to evaluate the performance of the water market. Each buyer of water, *b*, located at node *j* has a resale value, or benefit, schedule $B_{bj}(Q_{bj})$. In equilibrium, all buyers *b* at node *j* pay the same market price, P_j^*, and each buyer *b* earns a profit of:

$$\Pi_{bj}^* = B_{bj}(Q_{bj}^*) - P_j^* Q_{bj}^*, \tag{4}$$

where Q_{bj}^* is the equilibrium quantity of water delivered to buyer *b* at node *j*. Each seller of water, *s*, located at node *j*, has a cost schedule $C_{sj}(Q_{sj})$, and in equilibrium all sellers *s* at node *j* receive the same market price, P_j^*, and each seller *s* earns a profit of:

$$\Pi_{sj}^* = P_j^* Q_{sj}^* - C_{sj}(Q_{sj}^*). \tag{5}$$

Similarly, each transporter of water, *t*, located along arc *i*, has a cost schedule $C_{ti}(Q_{ti})$. His equilibrium earnings are also calculated using equation (5), with the subscripts *sj* replaced with the subscripts *ti*. Aggregate earnings for all buyers, Π_{Buy}^*, are the sum of the individual buyers' earnings:

$$\Pi_{Buy}^* = \sum_b \sum_j \Pi_{bj}^* \quad . \tag{6}$$

Aggregate seller earnings, Π_{Sell}^*, and aggregate transporter earnings, Π_{Xfr}^*, are defined similarly.

Note that the realized equilibrium values, denoted by the * superscript, are calculated by the computer based on the *submitted* bids and asks of each agent. As experimenters, we also know the true supply and demand schedules and can use these to calculate the competitive equilibrium prices, allocations, and earnings for each subject. The competitive equilibrium values will be denoted by replacing the superscript * with the superscript ^{ce}. Because the competitive equilibrium maximizes the possible gains from trade, we use this as a baseline against which the realized market outcomes can be compared.

Efficiency measures the ability of the market to extract all of the potential gains from trade. It is the share of potential surplus realized by the market:

$$(7) \qquad EFF = \frac{\Pi^*_{Buy} + \Pi^*_{Sell} + \Pi^*_{Xfr}}{\Pi^{ce}_{Buy} + \Pi^{ce}_{Sell} + \Pi^{ce}_{Xfr}} \quad \in \quad [0,1] \, .$$

The competitive equilibrium results in an allocation that maximizes the total possible surplus, thus, a perfectly competitive market will be 100 percent efficient. Table I lists the market efficiencies achieved in each of the 13 experiments computed as an average across all periods. Similarly, a measure of the individual performance of a particular subject is the ratio of the actual experimental earnings to the profits that would have been earned in the perfectly competitive equilibrium. Because individual subjects can earn super-competitive profits, it is possible that this ratio can exceed 100 percent for some (but not all) participants; however, the market efficiency, which includes all subjects' earnings, can never exceed 100 percent.

{INSERT TABLE I}

Contrary to our initial expectations, monopoly ownership of the conveyance facilities in Southern California actually improved market efficiency – from 88 percent under cotenancy to 91 percent. However, this result was largely driven by the outcome of a single experiment which averaged 62 percent efficiency over 24 periods. The startlingly low efficiency in this particular experiment was due to the one subject who represented Sacramento Valley Agriculture. This subject had rights to a substantial portion of the Sacramento River flows and could also consume this water at his location. For some reason, this subject elected not to sell or purchase substantial quantities of water at market prices that would have yielded large profits. In some periods, this subject failed to make a single trade. During the experiment, this individual earned less than half of the potential competitive equilibrium profits. Despite his behavior, the other subjects in this experiment performed reasonably well, averaging about 90 percent efficiency. Omitting the data from this experiment increases the average efficiency for the cotenancy experiments to 94 percent – which is consistent with the results from similar network experiments in natural gas and electric power.[4] This is even more remarkable in light of the fact that this water market network typifies what is commonly referred to as a "thin" market. This market is considered thin, not only because of the number of agents, but also because of their dispersion throughout the network, thereby creating a number of potential bilateral monopoly situations. Under such conditions, there is the potential for the market efficiency to be eroded by strategic behavior – similar to that witnessed in our experiments with monopoly control over conveyance.

To test whether the market efficiencies were due to subject behavior, rather than an artifact of the experimental design, we ran a series of simulations with zero-intelligence traders. These computer traders simply submitted bids and asks at random. Bids were drawn from a uniform distribution between zero and the actual resale value; asks were drawn from a uniform

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[4] A t-test of the null hypothesis that the efficiency of the cotenancy experiments (omitting the data from the one subject) exceeded the efficiency from the no cotenancy experiments is statistically significant at the one percent level.

distribution between the actual cost and the highest possible bid that could be submitted. Not surprisingly, the mode efficiency was low, between zero and five percent. Of more interest, however, was that in this thin water network, the maximum efficiency achieved over 10,000 simulated auctions was only 60 percent. That is, if everyone in the market submitted bids and asks randomly, the highest efficiency we would expect to achieve would be 60 percent. The fact that the observed efficiencies were significantly above this, suggests that these realized efficiencies can be attributed to subject behavior, not the structure of the experiment or the parameters used.[5]

Distribution of surplus is another measure of market performance. It measures the share of realized total surplus earned by a given individual, or group of individuals. For example, the percent of realized surplus, or profit share, of all the buyers is:

$$SHARE = \frac{\Pi^*_{Buy}}{\Pi^*_{Buy} + \Pi^*_{Sell} + \Pi^*_{Xfr}} \in [0,1]. \tag{8}$$

Table II reports the average profit shares for buyers, sellers and transporters. This table also lists the percent of competitive equilibrium profits earned by these groups on average. Of particular note is the transfer of surplus from sellers to buyers when monopoly control over conveyance is replaced with cotenancy. Although this transfer is small, only 3 percent, it is statistically significant (see the next to last column in Table III). This benefit to buyers accrues primarily to San Diego, which needs access to Metropolitan Water District's conveyance facilities in order to receive water deliveries. By creating competition on the lines, the price of water in San Diego drops about 20 percent, and the subject's earnings increase from less than half of the competitive

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[5] Thanks to Mark Olson, from Economic Science Laboratory, for running the zero-intelligence trader model.

equilibrium earnings to 84 percent. Conversely, the introduction of cotenancy reduces Metropolitan Water District's earnings by about 20 percent. Also noteworthy is the fact that the difference between the distribution of surplus for buyers and sellers under cotenancy and perfect competition is not statistically significant (see the first column in Table III).

{INSERT TABLES II and III}

Efficiency and surplus rely on measures of the gains from trade to evaluate market performance. Another important measure is the volatility of market prices. Table IV lists a few measures of the price volatility for each node type, and Table V summarizes the price volatility in Southern California. Figures 2 and 3 plot the average prices for each period at three Southern California locations.

{INSERT TABLES IV AND V}

{INSERT FIGURES 2 AND 3}

Overall, prices were rather stable with the variance diminishing in later periods, but the quantities traded sometimes fluctuated dramatically resulting in a number of missed trades, thereby reducing market efficiency.

On average, the market did not track the changes in water supply particularly well (see Figure 2), and it appears that this may be due to the high variance in the quantity traded. This variance seems to have created enough noise in the market to mask the supply cycle. To test this informally, we ran a pair of two-day experiments that eliminated much of the strategic behavior by having robots submit competitive bids and offers at all locations, except the Southern California nodes of interest (*i.e.*, Metropolitan Water District, San Diego, Colorado River Agriculture, and the conveyance channels that connect them). The subjects were aware of this revised market structure. This effectively created a reduced network with a more stable flow of water into Southern California. Figure 2 plots the actual prices for the second day of these two experiments. With the supply variability due to strategic behavior in Northern California eliminated, the prices tend to track the actual supply cycle rather well under cotenancy. However, these prices were slightly below the competitive prices, most likely because the buyers were able to take advantage of the robots that supplied the water at cost and did not react strategically. This phenomenon is well-documented in other experimental environments in which one side of the market is represented by robot traders (Kruse 1991). The price at San Diego fluctuated wildly with monopoly control because Metropolitan Water District set a high price that occasionally exceeded San Diego's ability to pay, resulting in no water being transferred into San Diego. In that experiment, MWD's strategy was quite successful; in the periods that San Diego was willing to pay the price, MWD's profits exceeded its competitive equilibrium earnings by 20 percent. Under cotenancy, however, this volatility disappears and more competitive outcomes result.

We suspect that the volatility in the quantity traded may be due partially to the institution and market information that subjects received. In particular, subjects knew the current market price and quantity at each node, but did not know the price at which they could be certain to induce an additional trade. It is a well-known characteristic of uniform price markets that naïve subjects tend to leave units untraded in a futile effort to manipulate price on the margin. Moreover, many subjects waited until the last few seconds of the period before submitting their bids and asks. During this time, the market would become extremely active as everyone rushed to beat the clock. This behavior tends to reduce UPDA to a sealed-bid auction, except that there is a chance that a last-second submission may not get processed on time. On the other hand, many subjects perceive that with earlier submissions, they risk revealing information that could potentially be used to their disadvantage.

There are many ways to improve the incentive for agents to enter their bids (and asks) earlier. For example, the Arizona Stock Exchange, applies a fee for entering bids that increases nonlinearly as closing time approaches. The institutional rules employed were simple, easy to explain to subjects, and sufficed to capture most of the potential gains from exchange. We would hone the rules to make marginal gains in efficiency if the case for market-based management were to succeed in the policy debates.

What do the results from these laboratory microeconomies tell us about the design of market institutions in the "real world"? The applicability of experimental results to the understanding of similar non-laboratory situations is referred to as parallelism (Smith 1980). Clearly, the experiments reported in this paper are a stylized representation of California's water network. However, the laboratory experiments allow us to learn about the water market institution in a simple environment that we can control. This permits us to build of body of evidence identifying the strengths and weaknesses of an institution, and provides an opportunity to develop modifications at a relatively low cost before implementation in the field. Thus, laboratory experiments can provide valuable insights to reduce the uncertainty inherently associated with the implementation of new institutions (also see Plott 1987).

6. Conclusions

This paper presents the results from the first of a series laboratory experiments designed to test alternative institutional arrangements for a computer-assisted spot water market, using California as a case study. Coordination problems and externalities have hampered the development of a truly competitive water market in California. Instead, during times of drought, California relies on a centrally-managed drought water bank to reallocate supplies. The assumption behind these water banks is that a truly competitive market cannot incorporate the myriad environmental and third-party impacts and is susceptible to manipulation by a few dominant players. According to the California Department of Water Resources, these factors necessitate a centrally-managed, regulated exchange mechanism to ensure an efficient and equitable allocation of water (California Department of Water Resources, 1994, pp. 188-191). The development of "smart," computer-assisted markets provides the ability to incorporate the same allocation criteria utilized by regulators, yet unlike the drought water banks, the prices in this institution provide information about the current state of the system, and therefore, it is able to adapt rapidly to new information. Laboratory experiments are valuable because they can be used to test these assumptions and evaluate alternative approaches to facilitating a reallocation of water that is consistent with social objectives (*e.g.*, economic efficiency, welfare distribution, environmental protection, etc.).

In these experiments, the 'smart' uniform price double auction yielded highly efficient outcomes, despite a rather thin market characterized by a limited set of trading opportunities for each agent. Efficiency increases when monopoly control over conveyance is replaced with cotenancy. The markets were somewhat volatile, especially in terms of quantity traded. Attempts to act strategically resulted in a number of foregone trading opportunities. Increasing the experience of the participants, as well as their numbers, even if just to the size of the recent California drought water banks, should improve efficiency and reduce volatility.

An experimental approach certainly has great promise for testing institutional variants to inform the public policy debate, and to familiarize decision-makers and principals with market mechanisms. It can form an evolving basis for an operational market. In addition to reducing coordination problems and the associated transaction costs, these “smart” markets may also have significant advantages over conventional bilateral markets in that they may save society costs associated with both the irreversibility of a poor policy commitment and the actual trial and error in implementing the market. Initial water markets are likely to be thin and require low transaction costs to become established. Properly designed markets can offer significant advantages under these situations.

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Table I. Realized Market Efficiencies

	Experiment	Observed Efficiency [a]	Adjusted Efficiency [b]
Cotenancy	01-co	84%	84%
	02-co	97%	97%
	03-co	86%	86%
	04-co	62%	--- [c]
	05-co	90%	90%
	06-co	99%	91% [d]
	07-co	99%	91% [d]
	Average	*88%*	*90%*
No Cotenancy	01-noco	93%	93%
	02-noco	85%	85%
	03-noco	74%	74%
	04-noco	98%	98%
	05-noco	99%	89% [d]
	06-noco	97%	67% [d]
	Average	*91%*	*84%*

a For each experiment, these are the average observed efficiencies across all periods.

b For each experiment, these are the average efficiencies across all periods, after making the noted adjustments.

c In this experiment, the anomalous behavior of one subject dramatically affected the efficiency. This observation is most likely an outlier, so we omit it from the adjusted calculations. This is discussed in more detail in section 5.

d In these four experiments, the high efficiencies are largely driven by the robot that simply revealed its WTP and WTA (see section 5 for explanation). The adjusted efficiencies do not include this robot, and report only the efficiency due to subject behavior.

Table II. Distribution of Surplus Among Buyers, Sellers and Transporters

	Percent of Realized Surplus (Market Share) [a]			Percent of CE Surplus [b]	
Activity	**Comp. Equilib. (A)**	**Cotenancy (B)**	**No Cotenancy (C)**	**Cotenancy (D)**	**No Cotenancy (E)**
Buyers	72%	70%	67%	86%	85%
Sellers	28%	29%	31%	91%	104%
Transporters	0%	1%	2%	150%	187%

[a] Percent of realized surplus is defined by equation (8) and is the ratio of the realized surplus for each group (*i.e.*, buyers, sellers, transporters) to the realized total surplus for all groups combined.

[b] Percent of competitive equilibrium surplus is the ratio of the realized surplus for each group (*i.e.*, buyers, sellers, transporters) to the competitive equilibrium surplus for that particular group. It is calculated similar to equation (7).

Table III. P-values for Hypothesis Tests Regarding the Distribution of Surplus in Table II

	Compare results to competitive equilibrium				**Compare cotenancy and no-cotenancy results**	
Activity	**H_0: B = A** [a]	**H_0: C = A** [b]	**H_0: D = 100%** [c]	**H_0: E = 100%** [d]	**H_0: B = C** [e]	**H_0: D = E** [f]
Buyers	0.12	0.00 *	0.00 *	0.00 *	0.02 *	0.59
Sellers	0.27	0.00 *	0.12	0.15	0.04 *	0.03 *
Transporters	0.00 *	0.00 *	0.00 *	0.00 *	0.61	0.66

The p-values reported here are from t-tests. The results from Wilcoxon signed rank tests are essentially the same.

* = reject H_0 at the 5% level of significance.

[a] H_0: Cotenancy percent of realized surplus (Table II, column B) equals competitive equilibrium percent of realized surplus (Table II, column A).

[b] H_0: No cotenancy percent of realized surplus (Table II, column C) equals competitive equilibrium percent of realized surplus (Table II, column A).

[c] H_0: Cotenancy percent of competitive equilibrium surplus (Table II, column D) equals 100%.

[d] H_0: No cotenancy percent of competitive equilibrium surplus (Table II, column E) equals 100%.

[e] H_0: Cotenancy percent of realized surplus (Table II, column B) equals the no cotenancy percent of realized surplus (Table II, column C).

[f] H_0: Cotenancy percent of competitive equilibrium surplus (Table II, column D) equals the no cotenancy percent of competitive equilibrium surplus (Table II, column E).

Table IV. Price Volatility

(measured in percent deviations)

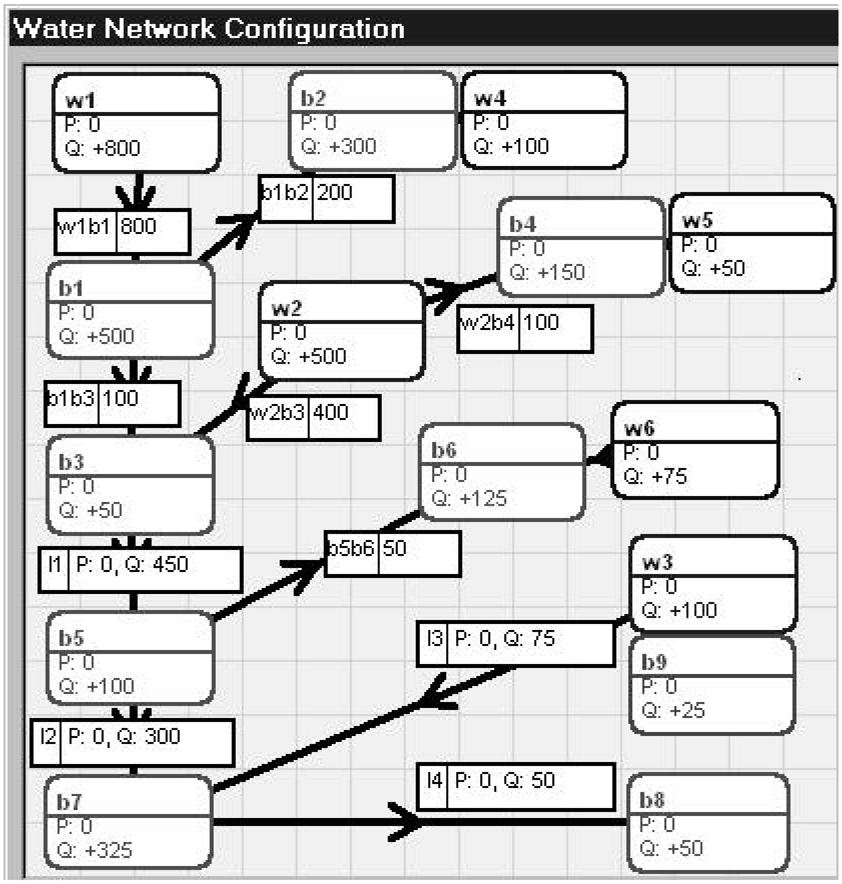
	COTENANCY			NO COTENANCY		
Node Type	Mean absolute deviation from CE	Standard deviation from CE	Standard deviation from mean	Mean absolute deviation from CE	Standard deviation from CE	Standard deviation from mean
Buy	0.28	0.48	0.48	0.28	0.49	0.39
Sell	0.27	0.43	0.62	0.29	0.54	0.40
Transport	1.15	2.46	0.64	1.60	3.94	0.56
All Types	0.57	1.47	0.58	0.55	1.82	0.43

Table V. Price Volatility at Southern California Locations

(measured in percent deviations)

		COTENANCY			NO COTENANCY		
Node Name	Node Type	Mean absolute deviation from CE	Standard deviation from CE	Standard deviation from mean	Mean absolute deviation from CE	Standard deviation from CE	Standard deviation from mean
Metropolitan W.D.	Buy	0.16	0.21	0.18	0.13	0.16	0.13
San Diego	Buy	0.19	0.27	0.21	0.32	0.41	0.22
Colorado River	Sell	0.29	0.34	0.32	0.28	0.33	0.31
Colorado Aqueduct	Transport	0.20	0.38	0.38	0.20	0.34	0.31
San Diego Aqueduct	Transport	2.67	3.97	0.90	5.66	7.84	0.89

Figure 1. Water Network Used in Experiments



The price and quantity figures in this network diagram are for demonstration purposes only and do not correspond to any experimental results. The alpha-numeric symbols in the diagram correspond to locations in California as follows:

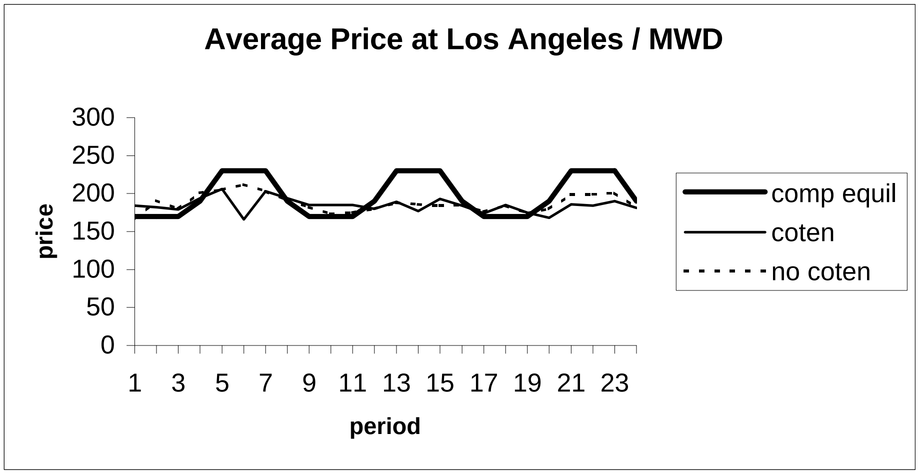
	Locations in network where subject was active					
	Consumption Nodes		Supply Nodes		Transport Links [a]	
Subject ID	Node ID	Node Name	Node ID	Node Name	Node ID	Node Name
1	B2	Sacramento Valley Agriculture	W1	Sacramento River		
			W4	Groundwater		
2	B4	S. San Joaquin Valley Ag.	W1	Sacramento River		
			W6	Groundwater		
3	B6	N. San Joaquin Valley Ag.	W2	San Joaquin River		
			W5	Groundwater		
4	B9	Colorado River Irrigators	W3	Colorado River	L3 [b]	Colorado River Aqueduct
					L4 [b]	San Diego Aqueduct
5	B1	Sacramento Urban				
6	B3	San Francisco Bay Area				
7	B5	San Joaquin Valley Cities				
8	B7	Metropolitan Water District			L3	Colorado River Aqueduct
					L4	San Diego Aqueduct
9	B8	San Diego			L3 [b]	Colorado River Aqueduct
					L4 [b]	San Diego Aqueduct
10					L1 [c]	Delta pumps
					L2 [c]	CVP/SWP canals

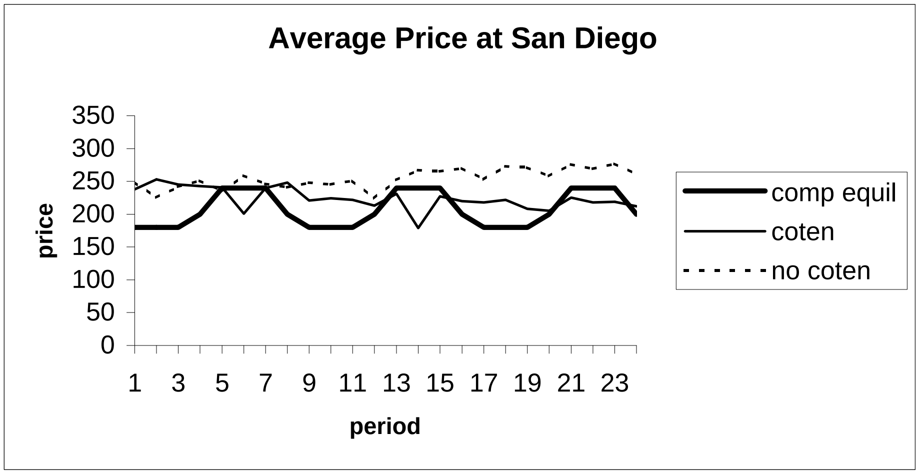
[a] The following transport links were supplies at zero cost in the experiments: W1B1, B1B2, B1B3, W2B3, W2B4, B5B6. For those links that actually do have conveyance costs, these costs were deducted from the induced values of the buyers at the destination.

[b] At nodes L3 and L4, subject numbers 4 and 9 had property rights to conveyance only during the cotenancy experiments. Without cotenancy, subject 8 had exclusive rights to the two canals.

[c] At nodes L1 and L2, subject number 10 is a robot that fully revealed its costs.

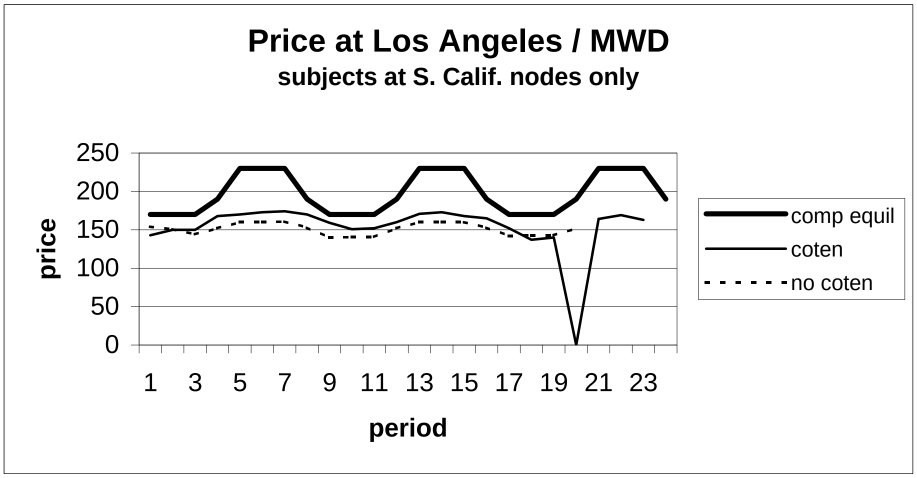
Figure 2. Average Prices at Southern California Nodes

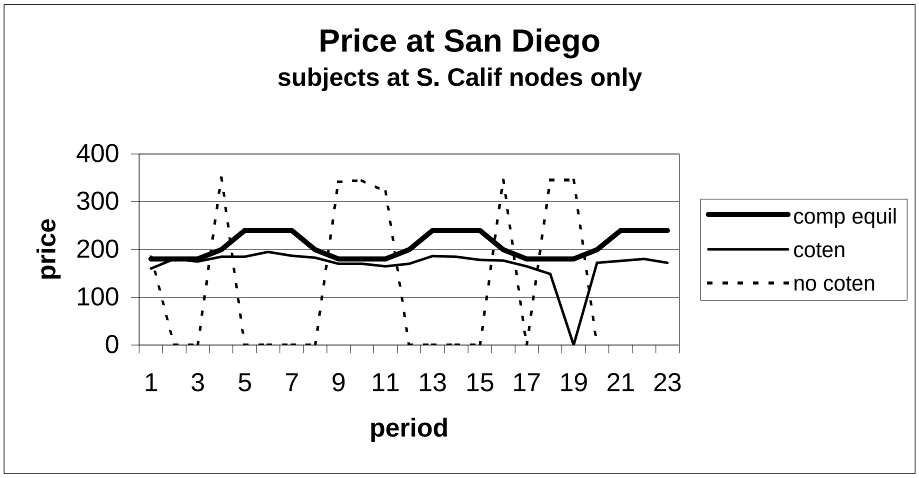




These are the average prices in each period from the seven cotenancy experiments, and six no cotenancy experiments.

Figure 3. Prices with Active Subjects at Southern California Nodes Only





These are the results from a pair of experiments in which there were only three active subjects, all other nodes were controlled by robots which submitted the actual costs and resale values. A price equal to zero means that no trade occurred.