The design of water markets when instream flows have value

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Abstract

The main objective of this paper is to design and test a decentralized exchange mechanism that generates the location-specific pricing necessary to achieve efficient allocations in the presence of instream flow values. Although a market-oriented approach has the potential to improve upon traditional command and control regulations, the questions remain about how these rights-based institutions can be implemented such that the potential gains from liberalized trade can be realized. This article uses laboratory experiments to test three different water market institutions designed to incorporate instream flow values into the allocation mechanism through active participation of an environmental trader. The smart, computer-coordinated market described herein offers the potential to significantly reduce coordination problems and transaction costs associated with finding mutually beneficial trades that satisfy environmental constraints. We find that direct environmental participation in the market can achieve highly efficient and stable outcomes, although the potential does exist for the environmental agent to influence outcomes.

1. Introduction

Voluntary water transfers have become an increasingly common mechanism for reallocating water in many of the world's arid regions. The potential efficiency gains from such transfers are well-documented (Vaux and Howitt 1984; Howe *et al.* 1986; Easter *et al.* 1998), and as advances in technology reduce transaction costs, market activity will continue to increase, particularly during periods of water shortages. However, the demand for water in consumptive uses has dramatically affected non-consumptive uses, such as native fish species that depend upon instream flows, and there are legitimate concerns about the adverse impacts that some transfers may generate, such as environmental degradation, third-party effects, and increased groundwater overdraft (e.g. Haddad 1999; Hanak 2005).

Because of the interdependence of the different water uses, the uncertainty about the impacts that may result from water transfers, and the complex coordination of water storage and conveyance, many water systems have been controlled primarily by state agencies, rather than market forces. Although centrally-managed institutions may help reduce the adverse impacts of water transfers, they can also impose high transaction costs and delays, and create uncertainties that may impede efficiency-improving transfers, particularly short-term leases or trades (Anderson and Snyder 1997). An alternative to centrally-dictated solutions is the formation of a water market that facilitates environmental participation such that these values are reflected in the allocation process. The concept of environmental participation in water markets is not new; there are a number of instances in which a private organization or government agency acquired water specifically for environmental purposes, including instream flows (e.g., Anderson and Snyder 1997; Burke *et al.* 2004; Colby 1990; Simon 1997; Tisdell and Harrison 1992). However, there is still considerable debate about whether and how water markets can be structured to incorporate instream flow demands. Both Huffman 1983 and Griffin and Hsu 1993 suggest that the creation of property rights for non-consumptive uses, such as instream flows, may lead to more efficient allocations. However, both Colby (1990) and Wahl (1990) express concerns that environmental participation may be insufficient to adequately reflect the full social value of these environmental benefits. Moreover, since the externalities associated with water transfers vary by location, efficiency will require location-specific pricing, which can introduce significant complexities and coordination challenges (Griffin and Hsu 1993; Weber 2001). In fact, a report to the California State Water Resources Control Board concluded that market forces alone cannot achieve efficient allocations because of the complex interrelations between the multitude of consumptive and non-consumptive uses and externalities not considered during private bargaining (Water Transfer Workgroup 2002).

Since a water market with spatially discriminative prices is likely to be complex and face high transaction costs associated with finding trading partners, institutional design plays an important role in the transmission of information and the evolution of prices such that the water market yields efficient allocations (Weber 2001). The development of “smart,” computer-coordinated markets offers the potential for decentralized solutions to these complex resource allocation problems. McCabe *et al.* (1989; 1991) have demonstrated the ability of these smart markets to achieve efficient allocations for natural gas and electric power. Dinar *et al.* (1998), Murphy *et al.* (2000) and Murphy *et al.* (2006) subsequently apply the smart market concept to spot water markets with similar success. We are aware of only a few other experimental analyses of water market institutions. Tisdell *et al.* (2004) investigate the impacts on water use resulting from the interaction of an environmental levy with community involvement. Garcia-Gallego *et al.* (2006) test how a monopoly, a duopoly and a public monopoly allocate two different qualities of water to farmers and consumers. Garrido (2007) uses experiments to test elements of a recent Spanish water reform. He finds that restrictions on trading between junior and senior rights holders leads to welfare losses and that defining rights to water stored in reservoirs would increase reservoir stock levels and provide more price stability. Cummings *et al.* (2004) used experiments to design and test an auction mechanism to compensate farmers to suspend irrigation during droughts.

This research uses laboratory experiments to design and test alternative property right structures that incorporate instream flow demands into a computer-coordinated spot market for the short-term water leases. Of particular interest are those situations in which accomplishing instream flow objectives does not necessarily require a reduction in the supply of water available for consumptive use. The nature of water rights and water use is such that multiple parties can derive benefits from the same units of water. This can create coordination challenges for any mechanism that facilitates water transfers. The water market mechanism described herein overcomes the coordination problems by using spatially discriminative prices that include the external costs of changes to instream flows, or more generally to any non-consumptive water use. Despite the inherent complexities of the market, participation in this mechanism is quite simple. Traders need only know and submit their value for water. A centralized computer then uses these offers to trade as the basis for determining allocations.

In the following sections, we discuss the impacts that environmental participation will have on market outcomes. The analysis has been structured such that the conclusions are applicable to any river system with instream flow values, or more generally any non-consumptive use. We find that environmental participation in the market can yield highly efficient allocations, although this efficiency tends to be slightly lower than observed under a more constrained baseline that does not allow active environmental participation. However, this lower efficiency in percentage terms does not necessarily imply that social welfare will decrease. That is to say, the flexibility afforded by environmental participation offers the opportunity to enjoy a slightly smaller slice of a larger pie. We also observe an increase in market volatility with environmental participation. This stems primarily from the non-consumptive nature of instream flows. Finally, the environmental agent is not a price taker in these markets and appears to have the ability to exercise some influence over the outcomes.

2. Approach

2.1 Water market institutions and instream flows

In order for any institution to allocate water efficiently, instream flow values must be incorporated into the allocation process (Griffin and Hsu 1993). To protect these instream values, the traditional command-and-control approach typically mandates a minimum flow through specified segments of the watercourse. Although these instream flow requirements guarantee some environmental protection, they provide little economic incentive to improve environmental quality, are unable to adapt quickly to new information, and rarely lead to efficient resource allocations (Weber 2001).

Although a market-oriented approach tends to be a more flexible alternative, the question remains how these rights-based institutions can be implemented such that the potential gains from liberalized trade can be realized. Griffin and Hsu 1993 introduce the concept of an Instream Flow District (IFD) or Environmental Trustee that represents the collective demand for instream flows along a section of the river. The IFD holds rights to instream flows along specific stream segments.[1] The IFD participates in the market by subsidizing transfers that yield benefits and accepting compensation for those that harm it. In the absence of explicit instream flow rights, these demands can be met either by subsidizing downstream consumption (as suggested by Griffin and Hsu 1993), or by purchasing and retiring upstream water rights. Note that the latter requires a net decrease in aggregate water consumption, whereas the former does not.

This article evaluates the relative merits of three different property right regimes designed to incorporate instream flow values into the allocation process: (1) minimum instream flow constraints without any active participation of instream flow interests; (2) no instream flow rights, but instream flow demands can be met by subsidizing downstream consumption; and (3) private property rights to instream flows. Following Griffin and Hsu 1993, we assume that instream flow values are represented by a single IFD that has complete information about the benefits of these flows.[2] For expository purposes, we will occasionally refer to these as environmental benefits, but this could include other instream values, such as recreational or aesthetic uses. We also assume that the IFD can achieve its environmental objectives with substitutes for instream flows. For example, the IFD might be willing to tolerate reduced instream flows in exchange for an investment in habitat improvements that yield improvements in environmental quality. Below we discuss the three alternative institutions considered in this article.

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[1] Others have also expressed an interest in creating instream flow property rights (Huffman 1983, Anderson and Johnson 1986, Livingston and Miller 1986), and the CalFed Bay-Delta program has proposed the creation of instream flow rights (Calfed Bay-Delta Program 1999, p. 3-8).

[2] Although the IFD has complete information about instream flow benefits, it has no information about the benefits and costs of water the other agents may have for consumptive uses.

2.1.1 A water market with environmental standards, but no instream flow participation (MinFlow)

This alternative is closest to existing institutions and is used primarily as a baseline against which the alternatives can be compared. Consumptive water users are free to trade, however, there is a minimum instream flow requirement that cannot be violated. Instream flow values are not explicitly accounted for in the allocation process, *i.e.*, the IFD is not active in this market. Thus, this institution guarantees a minimum level of environmental quality, but there is no mechanism for acquiring additional water to increase instream flows or accepting compensation for flow reductions. Although no one to our knowledge has studied the market effects of minimum flow constraints on the conveyance channels, our hypothesis is that this institution will remain highly competitive and should realize the maximum possible gains from trade given the instream flow constraints.

2.1.2 The Instream Flow District contributes to instream flow provision (IFDBid)

This institution is analogous to a situation in which the instream flow requirements, if any, are insufficient for meeting instream flow demands, and the IFD has the opportunity to induce supplemental flows by bidding for its provision. As long as the downstream buyers acquire water from the upstream source, the IFD will benefit from the instream flows. If the IFD voluntarily contributes to the cost of providing instream flows, she effectively subsidizes downstream consumption, thereby increasing flows. By coordinating with downstream buyers, rather than purchasing and retiring an upstream water right, the cost of instream flow provision for the IFD decreases. However, because the IFD benefits from instream flows regardless of its market participation, strategic incentives exist to under-reveal its willingness to pay for instream flow provision and free-ride off downstream consumption.

2.1.3 The Instream Flow District has private property rights to instream flows (IFDRights)

Minimum instream flow constraints are essentially a *de facto* property right that cannot be traded. Another approach to incorporating the instream flow demands into a water market is to recognize this by endowing the IFD with a transferable property right to this minimum level of instream flows. She would then have the option to allow the minimum flow requirement to be lower in exchange for compensation. Presumably this compensation would exceed the environmental damages incurred by the IFD (otherwise the IFD would not agree to the flow reduction); such a trade could result in a welfare gain while guaranteeing no environmental degradation. This potential to lease instream rights provides some added flexibility to the market by forcing the environmental trustee to evaluate the opportunity costs associated with holding these instream rights. From a policy perspective, a unique and particularly attractive feature of this institution is that it nests status quo. That is, if the IFD chooses not to participate in the market for whatever reason, the minimum instream flow requirements will remain in effect. The formation of non-consumptive instream flow rights also presents some important market design challenges. Huffman 1983, Anderson and Johnson 1986, Griffin and Hsu 1993, and Livingston and Miller 1986, among others, have expressed concern that if some form of instream flow rights were created, there may be the potential for the holder of the right (*e.g.*, the IFD) to extract rents from any upstream transfers and impair the transferability of existing water rights.

2.2 Experimental Design

We report the results from 11 experiments that were divided into the 3 treatments discussed in the previous section.[3] Subjects were recruited from the participants in the experiments by Murphy *et al.* 2000. They explained the instructions in a 30-minute presentation that included overheads with images from the various screens. After the trainer, their subjects participated in a two-day water market experiment. Hence, our subjects had experience trading in at least three prior water market experiments using the same software but different experimental design.[4] Before the start of the experiment, subjects were given five dollars for showing up on time. At the end of the experiment, subjects were paid their performance-based earnings in cash; these additional earnings ranged between $11 and $41.

Subjects were active as either buyers or the Instream Flow District. Water conveyance was costless and the water was injected into the network by a computer robot seller that simply revealed its supply costs. Each spot market experiment lasted about two hours. The session began with a pair of five-minute practice periods that was followed by 25 to 30 independent three-minute trading periods. The data from the practice periods were discarded. The parameters for the experiment were empirically derived using a calibrated non-linear programming model of regional agricultural production in California's Central Valley (U.S. Department of the Interior 1997).[5]

The experiments proceeded much like a standard double auction in which buyers submit bids, sellers submit offers, and a centralized exchange processes these bids and offers to

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[3] The original design called for 12 experiments. The data from one of the experiments was corrupted and unusable, hence we report the results of 11 experiments.

[4] The experiment was not context-free in the sense that subjects were aware that they were trading in a water market. While it is possible that this could have influenced their decisions, we doubt this was a major factor.

[5] Parameters are available at http://faculty.cbpp.uaa.alaska.edu/jmurphy/research.html.

determine a price that clears the market. The key difference is that prices in these experiments are location-specific. In addition, this exchange mechanism also incorporated the instream flow values into the allocation process. Subjects traded in a computer-assisted Uniform Price Double Auction (UPDA) similar to that described in McCabe *et al.* 1993 and subsequently applied to water markets by Murphy *et al.* 2000. As a price mechanism, UPDA's distinguishing feature is that all accepted bids to buy are 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 by the robot sellers are filled at a price greater than or equal to the highest accepted asking price. During each three-minute trading period, subjects could submit location-specific offers to trade as frequently as they wished, subject to an improvement rule that required that each new bid must be at a higher price or increased quantity than any previous submission. These price-quantity submissions represented the maximum price that the individual was willing to pay for the specified quantity of water. These submissions could be divided into as many as five separate price-quantity steps. After each new submission, the computer instantaneously recalculated the allocations using equations (1) to (3) below and reported the new prices and quantities for each node. Each subject knew the price and total quantity at each node in the network, as well as his or her market share, but did not know anything about the individual allocations of the other subjects. These allocations were tentative until the market was called after three minutes, at which time they became binding contracts, earnings were computed, and a new period began.

This computer-coordinated market maximizes total gains from exchange based on the submitted bids and offers, and determines allocations and prices at all nodes and conveyance channels. For any set of submitted bids and offers, the following network flow problem maximizes the realized surplus from trade:

$$\text{Maximize total surplus:} \qquad -\sum_i \hat{p}_i q_i + \sum_i \hat{v}_i q_i \tag{1}$$

subject to

$$\text{Balance of flow:} \qquad \sum_{i\in S_j} q_i = \sum_{i\in E_j} q_i \qquad (\forall \text{ nodes } j); \tag{2}$$

$$\text{Conveyance capacity} \qquad l_i \le q_i \le u_i \qquad (\forall \text{ arcs } i). \tag{3}$$

Each arc (*i*) in this formulation represents one bid or offer. If a buyer makes a multi-part bid, then it is represented by multiple parallel arcs connecting two nodes. Offers by the robot sellers are represented similarly. Thus, each bid or offer is represented by the vector $(s_i, e_i, l_i, u_i, \hat{p}_i)$ with s_i being its starting node, e_i its end node, l_i the least permissible flow on that arc, u_i the maximum flow on that arc (determined by the bid or offer quantity entered), $\hat{p}_i$ the submitted per-unit bid to buy or ask to sell flow on that arc (bids are represented as negative numbers, asks are positive), and $\hat{v}_i$ is the submitted bid for the nonconsumptive use of flow along that arc by the IFD. The quantity of water flowing on arc *i* is q_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, this constraint ensures that the market clears. Constraint set (3) ensures that the flow on each arc does not exceed the stated lower or upper bounds.

Each buyer, *k*, located at consumption node *j* derived a benefit $b_{kj}(\sum_{i\in E_j} q_{ki})$ from the quantity of water $q_{kj} = \sum_{i\in E_j} q_{ki}$ he consumed. His earnings (*i.e.*, consumer's surplus) were the difference between his consumption benefits and the cost of acquiring the water, $b_{kj}(q_{kj}) - p_j q_{kj}$, where p_j is the location-specific market price of water. Since each price-quantity step in an individual's bid is represented by a unique arc, the optimization algorithm treats flow through a river segment as a set of parallel arcs between two nodes. Let $Q_{kI} = \sum_{i \in (S_{\bar{j}}, E_{\underline{j}})} q_{ki}$ represent the total flow in river segment *I* starting at node $S_{\bar{j}}$ and ending at node $E_{\underline{j}}$ for subject *k*. The IFD derived a benefit $B_I\left(\sum_k Q_{kI}\right)$ from the total flow along river segment *I* regardless of whether she contributed to its provision. The means through which the IFD participated in the market distinguished the three different treatments.

2.3 Network Description

A schematic of the network used in the experiments is shown in Figure 1. This network provides a simple representation of a river system in which instream flows have value. This network has two river systems, only one of which contains a benefit for instream flows. There were three heterogeneous buyers of water at each of three buy nodes. (Subjects were randomly assigned roles). Node Buy-1 is located along the environmentally benign stream and node Buy-2 is located along the environmentally sensitive stream. These two systems converge downstream at consumption node Buy-3. In this network, buyers at Buy-1 and Buy-2 can only acquire water from a single source, but Buy-3 buyers can be supplied from both sources. This structure allows us to evaluate the potential impacts when some sources of water yield an instream flow benefit (from supply node Sell-2), and other sources do not (from supply node Sell-1). <INSERT FIGURE 1>

A single IFD is located on the environmentally sensitive stream at node Env. The non-consumptive instream flow benefits are an increasing function of the total flow along the segment connecting Buy-2 and Buy-3. The purpose of the Ocean node is to guarantee that the optimal solution to the network programming problem in equations 1 to 3 is feasible in the presence of a minimum flow constraint at the Env node.[6]

3. Results [7]

3.1 Efficiency

Both Colby 1990 and Wahl 1990 express concern that when the IFD does not have any property rights to flows (IFDBid), there may be an incentive to under-contribute to the provision of instream flows—the classic free-rider problem. On the other hand, some have noted that if the IFD has the property right to a minimum flow (IFDRights), it is possible that the IFD could try to extract rents by refusing to agree to compensated flow reductions (e.g., Griffin and Hsu 1993). Efficiency measures the ability of the market to extract all of the potential gains from trade. The perfectly competitive equilibrium results in an allocation that maximizes the gains from trade is therefore 100% efficient. In addition to reducing efficiency, these behaviors could affect market prices. We also evaluate prices in the market by asking two main questions: (1) Are the

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[6] At the instant trading begins, none of the buyers and sellers will have had a chance to submit their bids and asks, and the resulting allocations at that instant would be zero at every point in the network. If there are no minimum flow constraints, an instream flow of zero is not a problem for the optimization program. However, in the presence of a non-zero minimum flow constraint, a flow of zero is an infeasible solution to the linear program. In order to avoid this infeasibility problem, a robot buyer at the Ocean node submits bids for water at one experimental dollar above the cost of the water at Sell-2 for a quantity of water equal to the minimum flow constraint. If none of the other buyers in the market offers to purchase water, the robot buyer at the Ocean node will acquire sufficient water from node Sell-2 to satisfy the minimum flow requirement. This bid by the Ocean node does not compete with attempts by buyers to purchase water in the market—any bid by a buyer that exceeds the cost of a seller will still be accepted in the market. The Ocean bid only becomes a factor in the absence of such bids at the downstream node. In the perfectly competitive equilibrium, no water will flow to the Ocean node. The robot at the Ocean node is only active in the two institutions for which there is a minimum flow constraint.

[7] We dropped the results from the first two periods to control for learning and price discovery. This has no qualitative effect on our conclusions.

observed prices consistent with either the competitive equilibrium or strategic behavior on the part of the IFD? and (2) Regardless of the level to which prices converge, are these prices stable?

Result 1. *The MinFlow experiments quickly approach the perfectly competitive equilibrium with little variation.*

The structure of the MinFlow experiments is similar to other network flow experiments (McCabe *et al.* 1991; Murphy *et al.* 2000) that have produced highly competitive outcomes, so little reason exists *a priori* to expect that these sessions will yield different results. Table 1 presents some summary statistics of the observed efficiency for each of the three institutions. Not surprisingly, these experiments are almost perfectly competitive, with market efficiency quickly reaching 99 to 100% with almost no variation. In fact, the lowest observed efficiency in MinFlow was 95%. Because our baseline MinFlow experiments consistently yielded almost perfectly competitive outcomes, this institution serves as a useful benchmark for determining how allocations in the other two institutions are affected by the introduction of the IFD. If the other two institutions fail to produce similar results, we can reasonably infer that these deviations are due to IFD market participation. <INSERT TABLE 1>

Result 2. *All three institutions produced highly efficient outcomes that improve over time. However, IFD participation does produce a small, but statistically significant, reduction in efficiency. This effect is more pronounced for IFDBid.*

Although the efficiency of the two IFD institutions tends to be slightly lower than MinFlow, all three institutions generated results that are consistent with those from other computer-coordinated markets. McCabe *et al.* 1991, and Murphy *et al.* 2000 report efficiencies in the later periods ranging from 90 to 100% in the more competitively structured environments, and both the IFDBid and IFDRights experiments yield average efficiencies that fall within this range. Table 1 shows that average efficiency even in the early rounds is still quite high (91% for IFDBid and 97% for IFDRights). Moreover, after the first 10 periods, the number of periods with efficiency less than 90% is quite small for all three institutions, and average efficiency in the last half of the experiment exceeds 96% for each of the institutions. However, although the IFD institutions do achieve efficient outcomes on average, there is substantial variation, particularly in the early periods. Variability was greatest for IFDBid. <INSERT TABLE 2>

To test whether these differences in efficiency across institutions are statistically significant, Table 2 presents the results from a linear random effects model that estimates efficiency as a function of the institution and period while controlling for group-specific effects. IFDBid and IFDRights are dummy variables representing those two treatments, and ln(Period) is the natural log of period. We interact ln(Period) with the two IFD institutions to allow for the possibility that the rate of change in efficiency over time is different for each institution. All the coefficients in Table 2 are significant at the 1% level. The constant is interpreted as the efficiency for MinFlow in all periods—which is almost 100%. The model clearly indicates a statistically significant difference in the efficiency among the institutions. At the start of the experiment, the model predicts that the efficiency for IFDBid will be about 28 percentage points less than MinFlow, and efficiency IFDRights will be about 6 percentage points lower. However, the predicted efficiency for the last period of each institution is about the same.

If the “flexible” IFD institutions are slightly less efficient than the “constrained” MinFlow, does this suggest that the MinFlow institution is preferable in some economic sense? Not necessarily—by relaxing the minimum flow constraint, the IFD institutions provide the opportunity for total surplus to be greater than a market characterized by fixed constraints. (As long as the instream flow constraint is binding, the flexible IFDBid and IFDRights institutions will always offer higher potential total surpluses than MinFlow). Thus, although the IFD institutions are less efficient than MinFlow, it is quite possible that the realized total surplus in the IFD institutions will be greater than MinFlow. Essentially, the IFD institutions can yield a slightly smaller share of a potentially much bigger pie. In these experiments, the maximum possible total surplus under MinFlow is 91871. Under IFDBid, the maximum is 99971; with an average efficiency of 93 percent, the total surplus realized in this institution averaged about 92973, which still exceeds the maximum under MinFlow. From the experimental results, we cannot make any inferences about the magnitude of total surplus achieved in the IFD institutions relative to MinFlow in settings other than this series of experiments. This is an empirical question that depends largely on the share of total surplus represented by the different market sectors (buyers, sellers, IFD), the magnitude of the potential gain in efficiency that could result by incorporating the instream flow values into the market, and the elasticities of the supply and demand functions.

It is worth noting that the computer-coordinated market was able to achieve these high efficiencies even though only about 40% of the actual surplus was revealed through the submitted bids. To determine allocations, the submitted bids and asks are aggregated into individual demand and supply functions. These submitted values need not, and generally do not, correspond to the true willingness-to-pay and willingness-to-accept, an important question is whether incentives to under-reveal one’s true willingness to exchange will have any significant impact on the market outcomes. These smart markets demonstrate very high efficiency because, although intra-marginal units are greatly under-revealed, marginal units generally are not. These conditions are all that are required to achieve efficient allocations in uniform price market mechanisms (McCabe *et al.* 1989; 1991).

3.2 Price and volume of instream flows

Observed market prices provide another indicator of market performance. In this section, we compare the observed prices with two benchmarks: (1) the competitive equilibrium, and (2) the outcome assuming that the IFD is able to exert some influence over price. This latter outcome, denoted MaxIFD, is calculated by finding the price and quantity that would maximize IFD earnings assuming that all other players in the market are price takers.[8] In double auctions with a single seller (such as IFDRights), the support is weak for the monopoly price hypothesis (Smith *et al.* 1982), and in public goods experiments, pure free-riding behavior is rare (Ledyard 1995). Therefore, our *a priori* expectations were that it would be unlikely that the IFD would affect the market enough to reach the MaxIFD outcome, but that the IFD might exert sufficient influence such that a perfectly competitive outcome does not occur.

In all institutions, the market has three prices: upstream of the IFD (nodes Sell-2 and Buy-2 in Figure 1), downstream of the IFD (Sell-1, Buy-1, and Buy-3), and the price at the IFD's location (Env). For expositional simplicity, we will refer to the first two as the "upstream" and "downstream" prices, respectively. The price at Env is always the difference between these prices: $p_{Env} = p_{upstream} - p_{downstream} \geq 0$. This difference reflects either the contribution of the IFD to flow provision (IFDBid) or the price of reducing flows (IFDRights). We focus our discussion

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[8] In the case of IFDBid, the IFD could accomplish this by free-riding or subsidizing downstream consumption less than would be required in a perfectly competitive market. For IFDRights, the IFD could withhold supply by refraining from selling some of the rights to flow reductions.

of prices to node Env because that location highlights the wedge in prices caused by instream flow protection.

Result 3. *Prices for IFDBid and IFDRights are neither perfectly competitive nor IFD rent-maximizing. However, there is a clear difference in price patterns across sessions within a treatment, suggesting that outcomes may be sensitive to the decisions of the individual assigned the IFD role.*

Table 3 summarizes the prices at the Env node for each institution. As expected, the mean and median outcomes for the MinFlow institution are consistent with the competitive equilibrium. However, with IFD participation, observed prices tend to lie somewhere between the competitive and MaxIFD outcomes and are consistent with the conjecture that the IFD might withhold demand in IFDBid and withhold supply in IFDRights, but clearly not to the extreme under the MaxIFD outcome. <INSERT TABLE 3>

For example, in the IFDBid treatment, the competitive equilibrium price is \$15, but IFD earnings would be maximized with only a \$2 contribution to instream flow provision. On average, the observed prices lie roughly in the middle of this range; the 95% confidence interval is between \$7.68 and \$9.79. Both median confidence interval and t-tests indicate that this is below the competitive price, suggesting some degree of demand under-revelation, but not consistent with pure free-riding (\$2) either. Similarly, when the IFD can sell instream flow rights, there is some withholding of supply. The 95% confidence interval for observed price (\$16.90–18.77) lies between the competitive equilibrium (\$15) and the MaxIFD price (\$22). Again, median confidence interval and t-tests reject hypotheses about prices converging to either the competitive or the MaxIFD price.

In both treatments, the IFD typically (but not always) understated its willingness to trade. However, the degree of understatement varies by session. For example, in three of the IFDBid sessions, mean prices were about \$7. However, the fourth session had prices closer to the competitive equilibrium, with a mean of almost \$14. In two of the five IFDRights sessions, the pattern of offers and outcomes is consistent with a rent extraction story with average prices that exceed the \$22 MaxIFD price. On the other hand, two groups had mean prices below the \$15 competitive price. These differences across groups suggest that outcomes may be sensitive to the decisions of the individual who was randomly assigned the IFD role.

To test hypotheses about price while controlling for group effects, we use a linear random effects model; the results are presented in Table 4. The constant, 23.64, reflects the price of water at node Env in the MinFlow sessions. There is no statistically significant difference between this estimated price and the \$23 competitive equilibrium price for MinFlow.

The coefficients both for IFDRights and for IFDRights interacted with Period are not statistically significant, and a likelihood ratio test of the joint hypothesis IFDRights = Period × IFDRights = 0 is not rejected (χ^2=2.22, p=0.33). This suggests that there is no statistically significant difference between the prices in the MinFlow and IFDRights treatments; this would be consistent with the hypothesis that the IFD might withhold supply thereby raising prices above the \$15 competitive prediction.

For IFDBid, the results indicate a propensity to free-ride when the IFD contributes to instream flow provision. The coefficients for IFDBid and its interaction with price are statistically significant. We reject the hypothesis that the price is perfectly competitive (χ^2=4.38, p=0.04), but fail to reject the hypothesis that the price reaches the \$2 MaxIFD price (χ^2=1.00, p=0.32). Hence, the results for both IFD mechanisms indicate that it is possible for the IFD to exert some influence over prices. <INSERT TABLE 4>

Result 4. *IFD market participation increases price dispersion relative to MinFlow.*

A key concern in market design is whether prices will be stable, regardless of the level to which they converge. In the absence of any new information, *e.g.* a change in water supply, prices should not change. Large price fluctuations for no apparent reason would introduce an undesirable source of uncertainty into the market. Table 3 reports the overall standard deviation, and then decomposes this into between- and within-group effects. The between-group standard deviation provides an indication of the variability across different groups, whereas the within-group standard deviation reflects the price dispersion faced by a particular group of subjects. This latter metric is a useful gauge of the price dispersion within a particular market regardless of the level to which they converge. We focus primarily on this variability within a session because there are some clear differences in the price patterns across groups. For example, the mean price in session IFDBid03 was \$6.52, but for IFDBid04, the mean was \$13.78. Because of these group-specific differences, pooling all sessions would yield a misleading estimate of the price volatility faced by a particular group of subjects.

As expected, for MinFlow, the low standard deviations indicate relatively stable prices both within- and between groups, and 95% of the observed prices were between \$23 and \$25.[9] However, when the IFD participated in the market, prices within a group varied more, particularly for IFDBid. The within-group standard deviation for IFDBid was 4.07, which represents a substantial increase in price dispersion relative to MinFlow, particularly when using

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[9] Since the IFD was not active in this institution, the price at Env reflects the shadow value of the constraint and is the difference between the prices at the upstream and downstream locations.

the coefficient of variation to control for differences in means (0.08 vs. 0.47).[10] With IFDRights, there are some clear differences in mean prices across groups (the mean price for each of the five sessions is 23, 13, 11, 23, and 19). This is reflected in the relatively high between-group standard deviation. Even though each session tends toward a different price, the prices observed within a particular group are somewhat stable. The within-group standard deviation (2.44) and coefficient of variation (0.14) reflect a slight increase in the price dispersion within a particular market relative to MinFlow.

To get a sense of the relative magnitude of the price dispersion in the three institutions, we informally compared the within-group coefficients of variation observed in this data with that from Murphy *et al.* 2000. Their article does not allow IFD participation, but does permit subjects to actively trade rights to conveyance capacity at four locations. This is probably the closest parallel to our Env node. The coefficients of variation at the four conveyance channels are 0.44, 0.20, 0.32 and 0.58. This range is roughly consistent with that observed in the two IFD institutions, and would suggest that, although price dispersion increases with IFD market participation, the volatility appears comparable to that observed in other experimental water markets.

Result 5. *IFDRights yields higher levels of instream flows than IFDBid.*

Of the three institutions, instream flows at node Env are greatest under MinFlow. However, this binding 320 unit minimum flow constraint has an opportunity cost that reduces total social welfare. When the IFD can voluntarily agree to flow reductions in exchange for compensation (IFDRights), average flows drop to 293 (σ=33, 95% confidence interval 288–298). Both median

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[10] The coefficient of variation is the ratio of the standard deviation to the mean.

confidence interval and t-tests indicate that observed flows are greater than either the perfectly competitive flow level (244) or the MaxIFD flow (269). Although flows are lower than the 320 MinFlow constraint, these reductions are voluntary and compensated, thereby increasing social welfare with no adverse environmental consequences.

When the IFD has no instream flow rights and must contribute to flow provision, there is a noticeable reduction in flows. Mean flows at Env are 199 (σ=105, 95% confidence interval 177–220). This lies between the competitive flow level (244) and the MaxIFD flow (173). As with IFDRights, both median confidence interval and t-tests reject hypotheses about the equality of observed flows with respect to either benchmark. This would again suggest partial demand under-revelation at the margin.

4. Concluding remarks

The non-consumptive nature of instream flows presents challenges for market design and the structure of property rights. Successful implementation of an institution that can facilitate efficient water transfers requires a substantial amount of coordination to achieve an efficient water allocation, especially in the presence of interdependent uses. Our results indicate that computer-assisted markets offer the potential for addressing these challenges and generating highly efficient outcomes. Although facilitating IFD participation offers the potential for instream flow values to be reflected in the allocation decision, this can also create incentives for the IFD to misrepresent its true willingness to trade. When the evidence about efficiency and allocations are considered jointly, the results suggest that the IFD does appear to behave somewhat strategically, but not to the fullest extent possible. For both IFD institutions, outcomes tend to lie between the perfectly competitive and MaxIFD allocations. These outcomes are less stable than those observed under MinFlow and the patterns can vary across sessions. The efficiency losses with IFD market participation are relatively modest, with very high efficiency levels observed in all institutions particularly in the later periods. However, this small efficiency reduction may be partially a result of the experiment parameters: the IFD represents a relatively small share of the total surplus. From this, we conclude that the potential exists for the successful design of a market with IFD participation, but potential for strategic behavior must be carefully considered.

IFDRights offers a potentially appealing approach to the market-based management of instream flows. A particularly attractive feature of IFDRights is that it nests the status quo in the sense that, should the IFD choose not to participate in the market, the default minimum instream flow constraints will be maintained. Although flows may be lower in this institution relative to a fixed constraint on minimum flows, because these flow reductions are voluntary and compensated, all deviations from the status quo (i.e., binding flow constraints) are necessarily Pareto improving in the sense that no agent, including the environment, is made worse off. The market quickly converges to a competitive outcome, and prices and allocations are relatively stable. Moreover, IFDRights does not require additional revenue; instead it converts existing regulatory restrictions to tradable property rights. IFDBid, on the other hand, would require a source of funds with which it could finance its trading activities.

Finally, it is worth noting that the flow reductions under IFDRights reduce the amount of water available for downstream consumption. This increases the downstream price of water and reduces the upstream price. This price change under IFDRights benefits upstream buyers (node Buy-1) and downstream sellers (Sell-1), but reduces the welfare of downstream buyers (Buy-1 and Buy-3) and upstream sellers (Sell-2). Although this is the result of more efficient resource allocations, this could have regional economic impacts that may need to be resolved.

Table 1. Average market efficiency by institution

	Periods 3-15			Periods 16-30[a]		
Institution	**Mean**	**Std. Dev**	**95% Conf. Interval**	**Mean**	**Std. Dev**	**95% Conf. Interval**
MinFlow	99.7	1.1	(99.2, 100.1)	99.8	0.6	(99.6, 100.0)
IFDRights	97.3	3.6	(96.5, 98.2)	99.1	1.2	(98.8, 99.4)
IFDBid	90.6	11.3	(87.5, 93.7)	96.5	6.8	(94.3, 98.7)

[a] There were only 25 periods in IFDBid.

Table 2. Efficiency estimation results

Variable	Coefficient	Standard Error
Constant	99.74 ***	1.29
IFDBid	–28.01 ***	2.69
IFDRights	–5.93 ***	2.33
ln(Period) × IFDBid	8.60 ***	0.87
ln(Period) × IFDRights	1.69 ***	0.66

n=287. Likelihood ratio χ^2=100.68 (p=0.00). *** denotes significant at 1%.

Dependent variable is efficiency. Model estimated using a random effects model with each session as the random effect. A random effects tobit model, censored at 100, yields similar conclusions.

Table 3. Summary statistics for price at Env

				Standard Deviation		
Institution	**Comp. Eq.**	**MaxIFD**	**Mean**	**Overall**	**Between**	**Within**
MinFlow	23	n/a	23.64	1.89	0.25	1.88
IFDRights	15	22	17.84	5.62	5.63	2.44
IFDBid	15	2	8.74	5.06	3.43	4.07

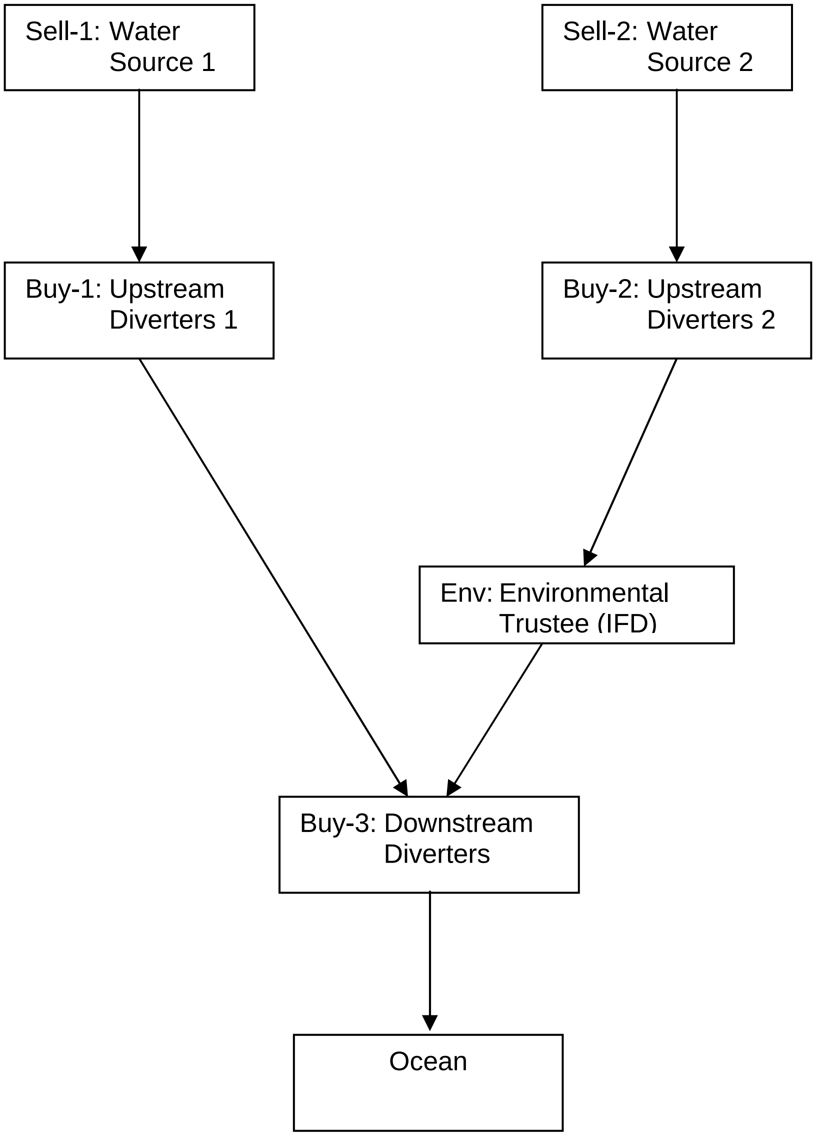
Table 4. Price estimation results

Variable	**Coefficient**	**Standard Error**
Constant	23.64 ***	3.39
IFDBid	–16.80 ***	4.21
IFDRights	–5.63	4.04
Period × IFDBid	0.14 ***	0.05
Period × IFDRights	–0.01	0.03

n=287. Likelihood ratio χ^2=23.21 (p=0.00). *** denotes significant at 1%.

Dependent variable is price. Model estimated using a random effects model with each session as the random effect.

Figure 1. The location of agents along the watercourse



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References

Anderson, T. and Snyder, P., 1997. Water markets: Priming the invisible pump. Cato Institute, Washington, DC.

Anderson, T.L. and Johnson, R.N., 1986. The problem of instream flows. Economic Inquiry 24, 535-554.

Burke, S.M., Adams, R.M. and Wallender, W.W., 2004. Water banks and environmental water demands: Case of the klamath project. Water Resources Research 40, W09S02.

Calfed Bay-Delta Program, 1999. Ecosystem restoration program, revised draft, vol. 6, water transfer program, CalFed Bay-Delta Program, Sacramento.

Colby, B., 1990. Enhancing instream flow benefits in an era of water marketing. Water Resources Research 26, 1113-1120.

Cummings, R., Holt, C. and Laury, S.K., 2004. Using laboratory experiments for policy making: An example from the georgia irrigation reduction auction. Journal of Policy Analysis and Management 23, 241-263.

Dinar, A., Howitt, R.E., Rassenti, S.J. and Smith, V.L., 1998, Development of water markets using experimental economics. In: K.W. Easter, M. Rosegrant and A. Dinar (Eds.), Markets for water potential and performance. Kluwer Academic Publishers, Boston.

Easter, K.W., Rosegrant, M.W. and Dinar, A., 1998. Markets for water: Potential and performance. Kluwer Academic Publishers, Norwell, MA.

Garcia-Gallego, A., Georgantzis, N. and Kujal, P., 2006, How do markets manage water resources? An experiment on resource market (de)centralization with endogenous quality, 6th Meeting on Game Theory and Practice, Zaragoza, Spain.

Garrido, A., 2007. Water markets design and evidence from experimental economics. Environmental and Resource Economics 38, 311-330.

Griffin, R.C. and Hsu, S.H., 1993. The potential for water market efficiency when instream flows have value. American Journal of Agricultural Economics 75, 292-303.

Haddad, B.M., 1999. Rivers of gold. Island Press, Washington, DC.

Hanak, E., 2005. Stopping the drain: Third-party responses to california's water market. Contemporary Economic Policy 23, 59-77.

Howe, C.W., Schurmeier, D.R. and Shaw, W.D., Jr., 1986. Innovative approaches to water allocation: The potential for water markets. Water Resources Research 22, 439-445.

Huffman, J., 1983, Instream water use: Public and private alternatives. In: T. Anderson (Ed.), Water rights: Scarce resource allocation, bureaucracy, and the environment. Pacific Institute for Public Policy Research, San Francisco, pp. 249-282.

Ledyard, J.O., 1995, Public goods: A survey of experimental research. In: J.H. Kagel and A.E. Roth (Eds.), The handbook of experimental economics. Princeton University Press, Princeton, NJ.

Livingston, M.L. and Miller, T.A., 1986. A framework for analyzing the impact of western instream water rights on choice domains: Transferability, externalities, and consumptive use. Land Economics 62, 269-277.

McCabe, K.A., Rassenti, S.J. and Smith, V.L., 1989. Designing 'smart' computer-assisted markets: An experimental auction for gas networks. European Journal of Political Economy 5, 259-283.

McCabe, K.A., Rassenti, S.J. and Smith, V.L., 1991. Smart computer-assisted markets. Science 254, 534-538.

McCabe, K.A., Rassenti, S.J. and Smith, V.L., 1993, Designing a uniform-price double auction. In: D. Friedman and J. Rust (Eds.), The double auction market: Institutions, theories, and evidence. Addison-Wesley, Reading, MA.

Murphy, J.J., Dinar, A., Howitt, R.E., Mastrangelo, E., Rassenti, S.J. and Smith, V.L., 2006, Mechanisms for addressing third-party impacts resulting from voluntary water transfers. In: J.A. List (Ed.), Using experimental methods in environmental and resource economics. Edward Elgar Publishing Ltd., Northampton, MA, pp. 91-112.

Murphy, J.J., Dinar, A., Howitt, R.E., Rassenti, S.J. and Smith, V.L., 2000. The design of 'smart' water market institutions using laboratory experiments. Environmental and Resource Economics 17, 375-394.

Simon, B.J., 1997. Federal acquisition of water through voluntary transactions for environmental purposes, US Department of the Interior - Office of Policy Analysis, Washington, DC.

Smith, V.L., Williams, A.W., Bratton, W.K. and Vannoni, M.G., 1982. Competitive market institutions: Double auctions vs. Sealed bid-offer auctions. American Economic Review 72, 58-77.

Tisdell, J.G. and Harrison, S.R., 1992. Estimating an optimal distribution of water entitlements. Water Resources Research 28, 3111-3117.

Tisdell, J.G., Ward, J.R. and Capon, T., 2004. Impact of communication and information on a complex heterogeneous closed water catchment environment. Water Resources Research 40, W09S03.01-W09S03.08.

U.S. Department of the Interior, 1997. Central valley project improvement act draft programmatic environmental impact statement. Technical appendix, Vol. 8, U.S. Department of the Interior, Bureau of Reclamation, Sacramento, CA.

Vaux, H.J., Jr. and Howitt, R.E., 1984. Managing water scarcity: An evaluation of interregional transfers. Water Resources Research 20, 785-792.

Wahl, R., 1990. Acquisition of water to maintain instream flows. Rivers 1, 195-206.

Water Transfer Workgroup, 2002. Water transfer issues in california, final report to the california state water resources control board, California State Water Resources Control Board, Sacramento, CA.

Weber, M.L., 2001. Markets for water rights under environmental constraints. Journal of Environmental Economics and Management 42, 53-64.

Appendix. Induced Values for Experiment Participants

Buyers and Sellers

		Steps				
Node		**1**	**2**	**3**	**4**	**5**
Water Sellers (robot)						
Sell-1	P	49	59	69	79	89
	Q	270	315	158	158	758
Sell-2	P	50	70	81	96	
	Q	190	123	155	200	
Agricultural Buyers						
Buy-1	P	154	126	101	84	74
	Q	133	22	22	22	67
	P	153	113	91	82	71
	Q	87	15	15	15	44
Buy-2	P	103	97	90	83	80
	Q	76	15	15	15	61
	P	109	101	94	88	85
	Q	49	10	10	10	39
	P	213	155	108	86	75
	Q	37	6	6	6	19
Buy-3	P	140	110	87	73	63
	Q	146	29	29	29	89
	P	121	100	88	76	67
	Q	121	24	24	24	65
Urban Buyers						
Buy-1	P	207	161	127	103	85
	Q	13	3	3	3	3
Buy-3	P	213	167	125	86	50
	Q	170	15	15	15	15

Instream Flow District and Robot Buyer

Institution	Node		Steps				
			1	2	3	4	5
Instream Flow District							
MinFlow	Env	P	Not applicable				
		Q					
IFDRights	Env	P	5	15	18	28	35
		Q	20	70	70	80	80
IFDBid	Env	P	35	28	18	15	5
		Q	80	80	70	70	700
Robot Buyer							
MinFlow & IFDRights	Ocean	P	82	71	51		
		Q	7	123	190		
IFDBid	Ocean	P	Not applicable				
		Q					