University of Massachusetts Amherst
Department of Resource Economics
Working Paper No. 2004-8
http://www.umass.edu/resec/workingpapers

Incorporating Instream Flow Values into a Water Market

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Abstract:

We use laboratory experiments to test three different water market institutions designed to incorporate instream flow values into the allocation. The institutions are (1) a baseline with fixed minimum flow constraints, (2) an environmental agent contributing to the cost of providing instream flows, and (3) creating an instream flow right in which an environmental agent can sell the right to reduced flows. Using a "smart" computer-coordinated market, we find that direct environmental participation in the market can achieve highly efficient and stable allocations. A particularly attractive and practical feature of the third institution is that it nests the status quo in the sense that, should the environmental agent 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.

Keywords: water markets, water transfers, instream flows, experiments

JEL Classification: C91, C92, H41, Q25

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Running title: Water markets and instream flows

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Acknowledgements
Funding for this research was provided by the National Science Foundation and the Environmental Protection Agency, joint grant number SBR-9513406, “Environmental Change and Adaptive Resource Markets: Computer-Assisted Markets for Water Allocation,” as part of the Human Dimensions of Global Climate Change Initiative; the John M. Olin Foundation; and the Charles H. Redd Foundation.

Incorporating Instream Flow Values into a Water Market

Abstract

We use laboratory experiments to test three different water market institutions designed to incorporate instream flow values into the allocation. The institutions are (1) a baseline with fixed minimum flow constraints, (2) an environmental agent contributing to the cost of providing instream flows, and (3) creating an instream flow right in which an environmental agent can sell the right to reduced flows. Using a "smart" computer-coordinated market, we find that direct environmental participation in the market can achieve highly efficient and stable allocations. A particularly attractive and practical feature of the third institution is that it nests the status quo in the sense that, should the environmental agent 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.

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; Howe, Schurmeier and Shaw; Easter, Rosegrant and Dinar), and as advances in technology reduce transaction costs, market activity will continue to increase, particularly during periods of water shortages. However, there are legitimate concerns about the adverse impacts that some transfers may generate such as environmental degradation, third-party effects, and increased groundwater overdraft. Moreover, despite the tremendous potential offered by water markets, the level of benefits realized from transfers is critically dependent upon the property rights and institutional rules that govern trading. A substantial body of literature already develops the theoretical issues regarding water markets. However, little research has been performed on the critical market design and implementation issues that are essential to realize these benefits. Economic theory says little about how different market institutions can affect allocations, yet 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; Kagel). Therefore, this article uses laboratory experiments to test three different "smart" water market institutions that incorporate instream flow values into the water allocation process.

The demand for water in consumptive uses has dramatically affected the environment, particularly for native fish species that depend upon instream flows. Environmental protection has been accomplished in a variety of ways in the western United States (see Landry; and Anderson and Snyder, for details on different state policies). Although the specifics of the state policies can vary significantly, they generally involve some form of centralized, government control over stream flows, typically as minimum instream flow requirements, combined with a regulatory review of proposed transfers.

One alternative to centrally dictated solutions to the water allocation problem is the formation of a water market that facilitates environmental participation. The concept of environmental participation in water markets is not new; there are a number of examples in which a private organization or government agency acquired water specifically for environmental purposes, including instream flows (e.g., Colby; Anderson and Snyder, Simon; and Burke, Adams and Wallender). Nevertheless, although movement exists towards some form of environmental participation in a water market, the debate about whether and how water markets can be structured to incorporate instream flow demands is still considerable. Both Colby, and Wahl express concern that despite this environmental market activity, it may be insufficient to adequately reflect the full social value of these instream flows. Moreover, achieving the socially efficient allocation would require substantial coordination, especially in the presence of both consumptive and non-consumptive uses (Weber; Griffin and Hsu).

Considering that substantial institutional change is often slow and costly to society, using laboratory experiments to design and test 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. 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.

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. The recent development of 'smart,' computer-coordinated markets provides the promise of developing decentralized solutions to such complex resource allocation problems. These markets allow decentralized agents, who best know their own circumstances and willingness to exchange, 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, typically an algorithm that maximizes the possible gains from exchange while observing constraints. By doing so, these markets can lower transaction costs, facilitate trades that may not have otherwise been effected, and increase overall market efficiency. The ability of these electronic markets to address complex allocation problems is a particularly attractive feature for water markets, especially in the presence of environmental and third-party impacts. McCabe, Rassenti and Smith have demonstrated the ability of these 'smart' markets to achieve efficient allocations in the natural gas and electricity industries. Dinar, et al., and Murphy, et al., subsequently apply the 'smart' market concept to spot water markets with similar success.

The research reported in this article 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 lease of water. 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 problems for any mechanism that facilitates water transfers. However, because computer-assisted markets combine the information and incentive advantages of decentralized ownership rights with the coordination advantages of centralized processing, these "smart" markets have the potential to facilitate efficient allocations, even in complicated environments.

In the following sections, we discuss the impacts that environmental participation will have on market outcomes. Although this research is motivated by California water issues, 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. In general, we find that environmental participation 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 the total 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 pure price taker in these markets, and appears to have the ability to exercise some influence over the outcomes.

Approach

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). To protect these instream values, the traditional command-and-control approach typically mandates a minimum flow through specified segments of the watercourse, and transfers that would violate the minimum flow constraints are prohibited. Although these minimum flow requirements will guarantee some environmental protection, they provide little economic incentive to improve environmental quality and rarely lead to efficient resource allocations. Moreover, command-and-control policies are often unable to adapt quickly to new information.

Market-oriented management strategies, on the other hand, tend to be more flexible alternatives than centralized control, yet the question remains how these property rights-based institutions can be implemented such that the potential gains from liberalized trade can be realized. Griffin and Hsu 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), 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 merits of three different property right regimes designed to incorporate instream flow values into the allocation process: (1) minimum instream flow constraints without any 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. We do not focus on the retirement of upstream water rights because in that case instream flows effectively become a consumptive use, similar to agricultural or urban uses. Dinar, et al. and Murphy, et al., discuss the design of water market institutions in the absence of interdependent, non-consumptive uses.

Following Griffin and Hsu, we will assume that instream flow demands are represented by a single IFD that has complete information about the social benefits of these flows. 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 at least comparable levels of environmental quality. Below we discuss the three alternative institutions considered in this article.

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

This alternative is closest to the existing institutions and is used primarily as a baseline against which the alternatives can be compared. Consumptive water users are free to trade, similar to the water market in Murphy, et al.. However, unlike Murphy, et al., 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 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.

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 Instream Flow District is responsible for inducing 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, regardless of whether the IFD contributes to its provision. However, by contributing to the cost of providing instream flows, the IFD effectively subsidizes downstream consumption, thereby inducing additional instream 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, incentives exist to under-reveal its willingness to pay for instream flow provision and free-ride off downstream consumption.

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

Minimum instream flow constraints are essentially a *de facto* environmental 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 Instream Flow District with a transferable property right to this minimum level of instream flows. They would then have the option to sell “flow reduction permits” which allow the minimum flow requirement to be lower. If the compensation resulting from any transfer that violated the instream right exceeded the environmental damages incurred by the IFD, relaxing the flow constraint by selling flow reduction permits could result in a social welfare gain while guaranteeing no environmental degradation. Moreover, assuming that the revenue received by the IFD is reinvested in environmental amenities, this mechanism can provide incentives to improve environmental quality. 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. This institution essentially converts the fixed minimum flow constraint to a cap-and-trade program.

The formation of non-consumptive instream flow rights also presents some important market design challenges. Huffman, Anderson and Johnson, Griffin and Hsu, and Livingston and Miller, 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.

Experimental Design

In this water market experiment, we use a version of the computer-assisted Uniform Price Double Auction (UPDA) detailed in McCabe, Rassenti and Smith and applied to water markets by Murphy, et al. 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 are filled at a price greater than or equal to the highest accepted asking price of sellers.

We report the results from 11 experiments that were divided into the 3 treatments discussed in the previous section.[2] Our subjects were recruited from the participants in the experiments reported by Murphy, et al. They first trained University of Arizona undergraduates in a two-hour session. To explain the experiment, subjects were given 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).[3] 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 profits ranged between \$11 and \$41.

All the experiments used a Windows-based application designed specifically for these water market experiments. This software (1) allows subjects to submit node-specific bids and asks, (2) displays the water network along with the tentative market price and quantity at each node, (3) informs subjects about which of their bids (or asks) were tentatively accepted at each node and computes profits, (4) provides market history data reporting the results of prior trading periods, (5) enforces the rules which define the institution, and (6) calculates the optimal resource allocations.

In this series of experiments, 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 that simply revealed its supply costs. Buyers' profits were calculated as the difference between the induced resale values given to the subjects and the actual price paid for the water in the market (*i.e.*, consumer's surplus). The IFD derived a benefit from any water flowing past his location – regardless of whether s/he contributed to its provision. The means through which the IFD participated in the market defined the three different treatments.

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).[4] These values were only known by the experimenter and the individual. The central computer was also unaware of these values; it used only the *submitted* bids and asks in determining the equilibrium allocations.

During each three-minute trading period, subjects could submit location-specific bids as frequently as they wished, subject to an improvement rule that required that each new bid to buy water must be at a higher price or increased quantity than any previous submission. Submitting a bid was costless. 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 equilibrium 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, profits were computed, and a new period began.

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 and conveyance channels. For any set of submitted bids and offers, solving the following network flow problem maximizes the realized surplus from trade:

$$\text{Maximize total surplus:} \qquad -\sum_{i} c_i f_i \; + \; \sum_{i} env_i f_i \tag{1}$$

subject to

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

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

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. 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), c_i the bid value or offer price per unit of flow on that arc (bid values are negative costs) and env_i is the environmental bid for flow along that arc. 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, 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.

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. Any changes in the streamflows on the other system are environmentally benign. There are multiple heterogeneous buyers of water at each of three locations. 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. With this network design, 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). Water is injected into the network at an increasing marginal cost by a "robot" that simply reveals these costs. <INSERT FIGURE 1>

The IFD is located on the environmentally sensitive stream at node Env. The non-consumptive instream flow benefits are an increasing function of the streamflow between nodes Buy-2 and Buy-3. The means by which the IFD can influence the flow at Env is the primary difference among the three institutions. 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.[5]

Results [6]

Efficiency

Both Colby and Wahl 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. Similarly, 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 withholding permits (e.g., Griffin and Hsu). In addition to reducing efficiency, these behaviors could affect market prices. Efficiency measures the ability of the market to extract all of the potential gains from trade, that is, it is the share of potential surplus realized by the market. The competitive equilibrium results in an allocation that maximizes the total possible surplus for a given institution and environment, thus, a perfectly competitive market will be 100% efficient. We also evaluate prices in the market by asking two main questions: (1) Are the 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, Rassenti and Smith; Murphy, et al.) that have produced highly competitive outcomes, so little reason exists *a priori* to expect that these sessions will yield different results. Figure 2 presents a scatter plot of the observed efficiency by period for each of the three institutions and Table 1 presents some summary statistics. 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 and FIGURE 2>

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, Rassenti and Smith, and Murphy, et al. 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, Figure 2 indicates that, although the IFD institutions do achieve efficient outcomes on average, there is substantial variation, particularly in the early periods. Volatility 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 because Figure 2 suggests that the rate of change in efficiency over time may be different for these institutions.

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. 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 smaller share of a 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 "smart" market was able to achieve these high efficiencies even though only about 40% of the actual surplus was revealed through the submitted bids. Since the reported individual demand and supply functions 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, Rassenti and Smith).

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 equilibrium assuming that the IFD is able to exert some influence over price. This latter equilibrium, denoted MaxIFD, is calculated by finding the price and quantity that would maximize IFD profits assuming that all other players in the market fully reveal their willingness to trade. In double auctions with a single seller (such as IFDRights), the support is weak for the monopoly price hypothesis (Smith, et al.). And, in public goods experiments, pure free-riding behavior is rare (Ledyard). Therefore, our *a priori* expectations were that it would be unlikely that the IFD would affect the market enough to reach the MaxIFD equilibrium, 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 (nodes Sell-1, Buy-1, and Buy-3), and the price at the

IFD's location (node 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 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 equilibria 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 equilibrium. <INSERT TABLE 3>

For example, in the IFDBid treatment, the competitive equilibrium price is $15, but IFD profits 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 flows 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 $2 MaxIFD price ($\chi^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.[7]

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 the coefficient of variation to control for differences in means (0.08 vs. 0.47).[8] 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. That article does not allow IFD participation, but it 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 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.

Concluding remarks

This article focuses on the impacts that two forms of IFD market participation will have on market efficiency, price dispersion and the maintenance of instream flows. 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 water transfers requires a substantial amount of coordination to achieve an efficient water allocation, especially in the presence of interdependent uses. A report for California's State Water Resources Control Board observes that an efficient water allocation must balance an "unusually complex mix of price responsive and non-price responsive social values" including complex interrelations between the multitude of consumptive and non-consumptive uses (Water Transfer Workgroup). They concluded that market forces alone cannot achieve efficient allocations because of the inherent complexities and externalities not considered during private bargaining. Our results indicate that computer-assisted markets offer the potential for addressing these concerns and generating highly efficient outcomes.

Facilitating IFD participation offers the potential for instream flow values to be reflected in the allocation decision, but at the same time, this can create incentives for the IFD to understate its 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. This would suggest that the extent of under-revelation might be sensitive to the decisions of the individual who was randomly assigned the role of IFD. 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. Moreover, the market quickly converges to a competitive outcome, and prices and allocations are relatively stable.

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

Institution	Periods 3-15			Periods 16-30[a]		
	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

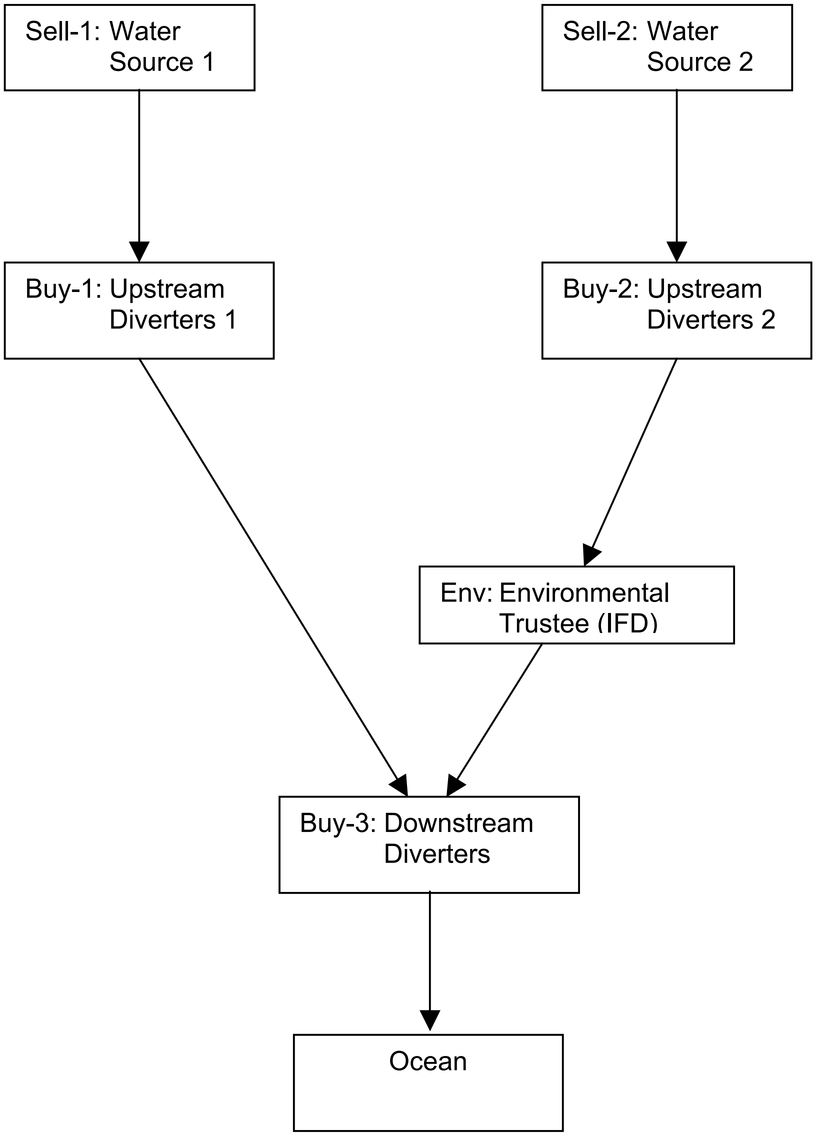
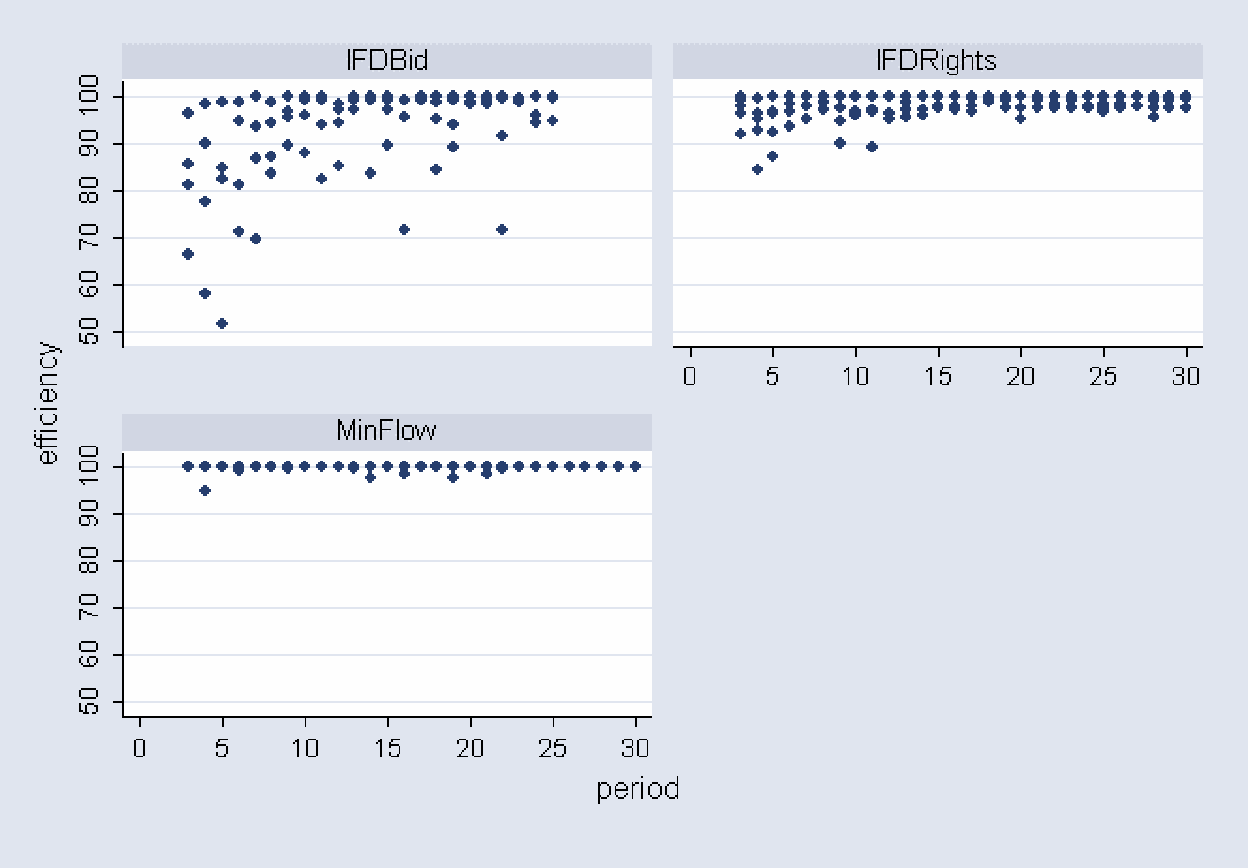


Figure 2. Efficiency by period for each treatment



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[1] Others have also expressed an interest in creating instream flow property rights (Huffman, Anderson and Johnson, Griffin and Hsu, Livingston and Miller), and the CalFed Bay-Delta program has proposed the creation of instream flow rights as a potential solution to this problem of instream flow provision in California's Sacramento-San Joaquin River system (CalFed Bay-Delta Program, p. 3-8).

[2] 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.

[3] 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.

[4] Parameters and details on their derivation are available upon request. <IN APPENDIX FOR REVIEW>

[5] At the instant that 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 will 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.

[6] We dropped the results from the first two periods to control for learning and price discovery.

[7] 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.

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

Appendix <FOR REVIEW ONLY>

Induced Values for Buyers and Sellers

Node[a]		Steps				
		1	2	3	4	5
		Water Sellers				
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

Induced Values for Instream Flows and the Ocean Node

Institution	Node[a]		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					