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(Abstract)

Economic studies have shown that when instream flow constraints are binding and surface water possesses public good characteristics, water transfers on the basis of consumptive use will lead to third party externalities and often entail high transaction costs. One major reason is the dominance of bilateral trading or multilateral trading having a high likelihood of strategic behavior. This paper proposes an alternative institutional arrangement called smart markets which maximize the aggregate efficiency gains from trading by allowing trades to be consummated through a common pool. The analytical model with instream flow constraints being binding, shows, that the shadow prices evolving from the centralized solution, incorporates the third party external costs imposed by any trader. Thus the financial burden of compensating victims who are affected by lower flows downstream or insufficient availability of water for diversions, are avoided.

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Key words: consumptive use rights; inflow stream rights; water rights markets; third-party externalities; computer-assisted smart markets

Pricing Mechanisms for Surface Water Rights: Trading With a Common Pool

Introduction

Due to water shortages and increased demand because of growing consumptive and aesthetic use, design of water markets is a topic of growing interest, both at a theoretical and practical level. The worldwide recognition of crucial non-consumptive uses in water-stressed regions has increased the policy discussions for intensive water resource management strategies. One policy solution gaining support is to assign water rights and make use of water rights markets because of the inherent gains to be realized from water rights trading (Murphy, et al. 2009).

Efficient use of resources requires that we appropriately define resource property rights. This is certainly true for surface water resources. Johnson et al. (1981) have argued that ". . . externalities resulting from ill-defined property rights are viewed as arising because water can be used and reused along a river basin. Transfer by one individual can affect return flow available to others" (Johnson, et al., 1981, p. 273). These authors concluded that the correct procedure is to quantify water rights on the basis of consumptive use and these rights should be fully transferable.

Consumptive use water rights are similar to any private good as long as none of the upstream flow constraints are binding. In this case, simple two-party exchange along the river or water course will not lead to the third-party impairment. Nonbinding flow constraints means that changing the ". . . location of a water right from the bottom to the head of the stream would not impair any of the consumptive use rights between points as total use has not been altered. Nor would there be insufficient flows at any point that would impair an existing user's ability to divert water in order to satisfy his consumptive use rights" (Anderson and Johnson, 1986, p. 541). The third-party externality arises when the flow constraints are binding and pair wise transactions prevent existing rights holders from being able to divert water to satisfy their consumptive use right. This third-party externality should be corrected with an appropriately designed compensation scheme. Moreover, the implied institutional structure based on pair-wise trades seems to not work well and a more appropriate type of institutional structure is needed.

The previous discussions cast surface water as a private good. But surface water has public good characteristics as well (Howitt and Hansen, 2005). Livingston and Miller (1986) as well as Loehman and Loomis (2008) noted the growing demand for recreation, aesthetics and species preservation and maintenance of natural environment, all of which are dependent upon water remaining in a stream and thus capturing the public good characteristics of surface flows. Valuing the public good characteristics of surface water is generally represented by the exercise of valuing instream flows. Nonmarket valuation techniques such as contingent valuation and travel cost methods have been used to measure recreational benefits of instream flows while the contingent valuation method has been used to estimate the value of instream flows to preserve native fish and a natural environment among other things (Loehman and Loomis, 2008). As a public good, instream flows are non-excludable, thus representing an additional form of externality problem which complicates the management of surface water flows even with the property right being defined as a consumptive use water right.

Anderson and Johnson (1986) have examined the problem of surface water allocation and instream flow rights in great detail. The general tendency has been to deny private parties the right to claim instream flows. This policy is usually implemented through a beneficial use of water requirement that establishes the legitimacy and extent of a water right in terms of the amount of water the property right owner has put to the beneficial use. This requirement is taken to mean that a right holder was expected to divert water from a river or watercourse and use it in an approved application.

The beneficial use requirement aspect of water right has been justified as a mechanism o discourage hoarding and speculation and to also encourage efficiency in the management of surface water resources (Griffin, 2006). There are three problems with the beneficial use requirement. First, there is the emphasis on only approving those water uses that revolve around physical diversions. Second, ". . .given that most western streams are fully appropriated . . . the possibilities of hoarding and speculation are remote" (Griffin, 2006, p. 125). Finally, the beneficial use requirement limits the transferability characteristic of the water right which in turn reduces the economic efficiencies that can be gained from allowing voluntary property right trades.

The previous discussions raise a lot of questions about the role a market can realistically play in finding an efficient allocation of surface water resources even with the property right properly defined. For instance, Griffin and Hsu (1993) note that the public good character of instream water use and the absence of proper interface between instream users and diverters result in the under allocation of water for instream purposes. The current market structure relies heavily on pair-wise voluntary exchanges. These types of trades are problematic in that suppliers and consumers face high transaction costs and do not yield efficient allocations of surface water resources in more realistic settings.

The contributions of our paper are as follows. The consumptive use right for surface water represents a clearly defined property right. As noted previously, bilateral trades of consumptive use rights are similar to any private good as long as no upstream flow constraints are binding. If any of the upstream flow constraints are binding, bilateral trading of consumptive use rights leads to third party impairment or externalities and the third parties impacted by these bilateral trades in this case are not appropriately compensated. For our first contribution to the literature, we design a market institution where consumptive use rights trades take place through a common pool instead of bilaterally. This system does not require that traders be matched up since trading is with the common pool. The prices in our system are based on key shadow prices which reflect each trader's impact on the availability of water withdrawals for consumptive use for all decisions makers along the river. The third-party externalities are resolved in this system because potential third parties are appropriately compensated. Our second contribution is to extend the common pool trading mechanism to include the demand for Instream flows which are assumed to take on public good characteristics. The third contribution of our work is a trading system that leads to significant reduction in the transaction cost of trading consumptive use water rights.

The remaining parts of this paper are organized as follows. First, we present a brief discussion of smart market models found in the literature. Next, present the theoretical "smart-market" model where a surface water right is classified on the basis of consumptive use and is treated solely as a private good. We assume throughout this paper that all rights holders have equal standing and do not consider water right systems where the rights are prioritized. We also assume there decision makers face no capacity constraints when the divert water from the river or water course. Subsequently we derive a set of pricing rules for the consumptive use right. The model is then extended to include the demand for instream flows and the presence of the public goods characteristics of surface water. The pricing rules for the extended model are derived. We close the paper with an examination of issues related to the practical implementation of these types of models.

Literature Review—The Use of Smart Market Models

Models where trading items such as permits are based on trading with a common pool are also known as smart markets (McCabe, et al., 1991). The concept of a central market coordinator plays an important role in the formulation and implementation of a smart market. The market coordinator can provide a list of prices to market participants and ask each participant to submit bids and offers for each of these prices. The market manager then uses the submitted bids and offer schedules in an optimization algorithm to find prices and rights allocations that maximize net gains from trade. The market can be a periodic auction that is cleared using mathematical programming techniques such as linear programming. Water rights pricing information is based on a range of shadow prices generated for the mathematical programming model. The market manager operates the smart market, and all trades are with the market pool rather than bilateral trades. These markets are particularly useful when trades are likely to have significant transaction costs.

The computer-assisted smart markets have been used in the wholesale electricity markets in New Zealand (Alvey, et al., 1998) as well as in natural gas markets (McCabe, et al., 1991). Prabodanie et al (2010) have applied computer-assisted smart market models to water quality management problems while Willett et al. (2013) developed a computer-assisted smart market for an air quality problem. Becker (1995), in work related to smart markets, used shadow prices based on a similar type of model structure to consider the value of moving from central planning to a market systems on the example of the Israeli water sector. Zeitouni et al., (1994) used mathematical programming models to represent water market mechanisms with applications to the Middle East.

Computer-assisted smart market models have also been applied to water allocation problems. Murphy et al. (2000) reported a smart market for allocating surface water. The smart market model structure was based on delivering water through a simple pipeline-like network. The model was simulated with students who make bids in a laboratory setting. The smart market was applied also using a case study of the California water transfer system in the United States. The market transactions modeled were water allocations and water transportation capacity rights. The pricing mechanism was based on the sealed bid price double auction mechanism. Murphy et al (2006) extended the smart market model structure based on the work reported in 2000 to include policies that addressed third-party impacts resulting from voluntary water transfers. Two different policies were proposed. The first one allowed water rights holders to participate in market transactions if they were to experience third party impacts from voluntary trades. This policy had the advantage of allowing third-party impacts to trade, but was also subject to strategic behavior and free riding activities that were likely to erode efficiency gains. This policy was also likely to include high transaction costs. The second policy examined was based on taxing water transfers to compensate victims experiencing third party effects. This policy seemed to involve complex procedures along with high transaction costs.

To address these shortcomings, Murphy et al (2009) described three institutional arrangements to assign instream flows under water market mechanisms and looked at the difference across these arrangements in terms of efficiency, prices, and instream flows.

The first institutional arrangement was a water market with environmental standards but with instream flow participation, where consumptive users trade water allowing for a minimum instream flow (MiniFlow) that cannot be violated. This led to high gains from trade, provided the instream flow is adequate. The second arrangement was to have an Instream Flow District (IFD) that contributed to instream flow provisions. The IFD had the power to change the instream flow requirements by becoming an active actor in the water market—it could either buy water directly for instream flows from upstream users or it could coordinate with the downstream users and therefore guarantee the instream flow at a lower cost. Some strategic behavior resulted from this arrangement because IFD understated its willingness to pay for the provision of instream flows. Finally, in the third arrangement, the IFD was designed to have property rights on the minimum water requirement for instream flows and could adjust it in exchange for a compensation, to cover the damages caused by lower instream flows.

Results from the experimental economics exercises, using computer assisted smart markets, showed that Mini-Flow approached perfectly competitive equilibrium to a larger extent, following other findings by McCabe et al (1991) and Murphy et al (2000). All three settings produced highly efficient outcomes which improved over time, but the inclusion of IFD in these water markets had a negative statistically significant impact on efficiency, but led to higher social surplus in the long run over MiniFlow. Although, IFD participation increased price dispersion with respect to Miniflow it led to higher levels of instream flows than IFD.

Unfortunately, the institutions and policy options we have noted above are designed in such a manner to make them overly complex and involve significantly high transaction costs. We propose an alternative institutional market design for surface water transactions where the consideration of a central market manager and water trading based on consumptive use rights avoid the transaction cost problem to a large extent. We employ an uniform set of bids and offers with homogenous users, where the market manager decides upon the optimal prices and quantities to be traded. Secondly the permit prices are calculated assuming that permits are based on consumptive use rights at each location. Moreover, market-based compensation for water allocation decisions evolves from the optimization model solution.

Smart Market Model for Consumptive Use Rights

The purpose of this section is to consider material that is used in the computer-assisted smart market formulation. Following the discussions in Johnson et al. (1983), Johnson and Gisser (1983), and Anderson and Johnson (1986), we define a water right on the basis of the consumptive use. The model constraint set includes a set of flow constraints similar to those found in Johnson, et al. (1981), Anderson and Johnson (1986) as well as in Weber (2000). The model in this section considers only water that is diverted for consumptive use and ignores the presence of instream flows for the moment. The basic model is extended to include the presence of instream flows. Two different policy options will be considered in the extended version of the model with instream flows.

We assume that users located on a river have a well-defined decision problem that yields a demand schedule for water rights. This demand function is assumed to take the form of a value of marginal product function for the consumptive water use. The value of marginal product function can vary for each type of use where the possible uses include agriculture, municipal and industrial uses (Johnson, et al., 1981). We assume that the bid function for each user of water as it is communicated to the market manager becomes a discrete function. These bid functions are described in more detail below.

We first introduce a number of important features of the river system before formally presenting the smart market model structure. The set of users along the river are ordered as $(i = 1, \dots, I)$ by the increasing distance from the river source. The water flows at the river source are denoted as V_0. The amount of water at any location i available for diversion is V_i and depends on the upstream consumption. The constraint set for each diversion point in our model is similar to those found in Johnson et al. (1981), Johnson and Gisser (1983) and Anderson and Johnson (1986).

We consider first diversions of water and the corresponding consumptive use at some point i. Let s_i represent the consumptive use of water at point i and Y_i the amount of water diverted at point i. Denote the exogenous fraction of water returned to the river at point as R_i with $0 < R_i < 1$. The amount of water available for diversion at location i is represented by the following first order equation:

$$V_{i+1} - V_i = -(1 - R_i)Y_i \tag{1}$$
$$(i = 1, \dots, I)$$

Consumptive use rights for surface water at location i is

$$s_i = (1 - R_i)Y_i \tag{2}$$
$$(i = 1, \dots, I)$$

Let j also denote a diversion location along the river. We can use equation (2) to rewrite equation (1) for any diversion point i along the river as follows

$$V_i = V_0 - \sum_{j=1}^{i-1} s_j \tag{3}$$

The pricing mechanism and institutional structure we use for pricing and distributing water rights is called a computer-assisted smart market. First, each market participant determines a bid or offer schedule for surface water rights for a range of possible prices by solving its own version of a decision problem. A key component of this market institution is the market manager. This individual provides the market with a range of prices for water rights and each decision maker responds by giving the market manager a quantity of water rights to buy or sell at each possible price. The market manager issues a final call for bids and then makes an announcement that the market has closed and no bids are to be accepted at that point. The market manager then applies an optimization algorithm to the submitted bid-offer messages to determine those prices and water rights allocations that maximize the gains from trades subject to an appropriately defined constraint set. The market manager next settles all market transactions. All trading in this system is with the common pool and bilateral trades are not allowed. Trading with the common pool is a key feature of our institutional design and significantly reduces the transaction costs.

The smart market model can be specified as a net pool or gross pool market. The net pool market assumes each market participant has an initial allocation of permits and provides a separate offer curve to sell permits and a separate curve to buy more permits. In contrast, the gross pool market ignores any initial holding water rights in the model. Theoretically, there is no difference between the two formulations and the gross pool market is easier to work with (Raffensperger, 2009). The gross pool market model is always mathematically feasible and any issues regarding the buys, the sells, or the initial distribution of permits in the smart market model are resolved as part of the financial settlement once the smart market is solved. Montgomery (1972) has rigorously shown that instantaneous multilateral permit trading yields competitive market equilibrium. It is also concluded that the market equilibrium is independent of the initial allocation of water rights as well as any redistributions of rights as long as transaction costs are low. We assume that the smart market model is a gross pool market which means there are no initial holdings of water rights and all market participants purchase rights from the market manager. We also assume the market manager keeps the revenue earned from the auction.

The basic structure of the smart market for water rights is presented in the following paragraphs. First, we assume that the bid functions for each bidder are represented by discrete functions where each step is called a tranche. The index for each bidder's tranche is denoted as k $(k = 1, \dots, K)$. Let B_{ik} represent the size (quantity of water rights) of the bid tranche k submitted by bidder i. P_{ik}^{b} is the price specified in bid tranche k submitted by bidder i and s_{ik}^{b} the quantity of consumptive use rights accepted from bid tranche k by bidder i.

The formal structure of the smart market model for consumptive use water rights is presented as follows:

$$\text{Max} \qquad \mathrm{R} = \sum_{i=1}^{I} \sum_{k=1}^{K} P_{ik}^{b} s_{ik}^{b} \tag{4}$$

Subject to

$$\sum_{\boldsymbol{k=1}}^{\boldsymbol{K}} s_{ik}^{b} = s_i \qquad (\pi_i)(5)$$

$$(i = 1, \dots I)$$

$$\sum_{i=1}^{I} s_i \leq \bar{s} \qquad (\pi)(6)$$

$$s_{ik}^{b} \leq B_{ik} \qquad (\theta_{ik})(7)$$

$$(k = 1, \dots K)$$
$$(i = 1, \dots I)$$

$$-s_{ik}^{b} \leq 0 \qquad (\phi_{ik})(8)$$

$$(k = 1, \dots, K)$$
$$(i = 1, \dots I)$$

$$\frac{s_1}{(1 - R_1)} \leq V_0 \qquad (\lambda_1)(9)$$

$$\frac{s_i}{(1 - R_i)} \leq V_o - \sum_{j=1}^{i-1} s_j \qquad (\lambda_i)(10)$$

$$(i = 2, \dots, I)$$

$$\tilde{V} \leq V_0 - \left[\sum_{i=1}^{I} s_i\right] \qquad (\sigma)\ (11)$$

The variables in parentheses of equations $(5) - (11)$ are Lagrangean multipliers.

The objective function equation (4) represents the net benefits from trading consumptive use water rights assuming the constraint on the number of water rights issued by the central market manager as well as the flow constraints at each diversion point is satisfied. Recall the mathematical programming model is formulated as a gross pool market and the market equilibrium for this model is independent of the initial distribution of permits (Prabodanie, et al., 2011). The mathematical programming model is solved, the optimal quantities of consumptive use rights and the respective quantity of water rights are determined for each market participant. Payments to the central market manager for water rights purchases are completed.

The coefficient P_{ik}^{b} in the objective function equation (4) shows how much each block of water rights is worth to an individual bidder. Equation (5) is an allocation constraint which shows the quantity of water rights accepted and the final water rights position. Constraint (7) imposes an upper bound on each tranche, making sure that the quantity of water rights cleared does not exceed the maximum specified by the bidder. Constraint (8) requires that the number of water rights accepted in each bid tranche must be positive. Constraint (6) states that the total number of consumptive use surface water rights traded cannot exceed the total number of water rights issued by the market manager. Constraints (9) and (10) are flow constraints which limit the amount of water that can be diverted at each point along the river. Constraint (11) indicates that a minimum amount of water must remain at the end of the river diversion points. The value of $\tilde{V}$ is frequently established by water compacts. Such agreements would apply if, for example, the end point of the river was a state or country boundary.

Water Permit Prices for Consumptive Use Rights

The information on the market-clearing prices for waters when instream flows are not specified, can be found from the first order conditions of the smart market derivations which are shown in the appendix A. The relevant conditions are the following:

$$P_{ik}^{b} - \pi_i - \theta_{ik} + \phi_{ik} \leq 0 \tag{12}$$

$$(k = 1, \dots, K)$$
$$(i = 1, \dots, I)$$

$$\pi_i - \pi - \frac{\lambda_i}{(1 - R_i)} - \sum_{j=i+1}^{I} \lambda_j - \sigma \leq 0 \tag{13}$$

$$(i = 1, \dots, I)$$

The shadow prices related to the smart market model constraints yield a number of important interpretations and are the foundation of the consumptive use permit prices. Initially we assume that flow constraints (including the last constraint at the end of the water course) are nonbinding. We can now conclude that

$$\pi_i = \pi \tag{14}$$

for all $i(i = 1, \ldots, I)$. This shadow price indicates the increase in net benefits of consumptive use rights if the manager increases the number of permits $\bar{s}$ by one unit. We interpret this shadow price as the market-clearing price for consumptive use permits and in this case all consumptive water users pay the same price for a water right traded. In this case, the only binding constraint is the constraint involving the number of consumptive use permits available in the market. The market manager charges each firm in the permit market the same price based on the value of this shadow price. For the remainder of the discussions, we assume that constraint (6) is binding.

Let us next that assume all flow constraints are binding at all i diversion points along with the flow constraint at the end of the water course. Equation (13) is then restated as follows:

$$\pi_i = \pi + \frac{\lambda_i}{(1 - R_i)} + \sum_{j=i+1}^{I} \lambda_j + \sigma \tag{15}$$

$$(i = 1, \ldots, I)$$

First, note that equation (15) shows that all i firms along the river participating in the water rights market pay a multipart price in our version of a smart market. The first part of the multipart price is π which represents the price for each consumptive use permit. The second term is the marginal opportunity cost for firm i to divert water from the river at its location along the river when the flow constraint at that location is binding. The third set of terms represents the marginal opportunity cost firm i imposes on the firms downstream with its consumptive of water when the downstream flow constraints are binding at the various diversion locations. In particular, the λ_j

$(j = i + 1, \dots, I)$ reflect the marginal opportunity cost that consumptive use by firm i imposes on downstream water user $j$when the flow constraint at that diversion point is binding. Notice that λ_j being nonzero means that the possible third-party impacts associated with voluntary water permit trades are internalized in the marginal opportunity cost price paid by each of the permit traders. The shadow price σ is the marginal opportunity cost of a binding flow constraint at the end of the water course.

The shadow price with the allocation constraint (5) shows how much the objective function equation (4) increases if firm i receives one additional consumptive use right permit. Each Instream flow permit holder pays the value ψ_i for each Instream flow right, but prices paid or received may differ for individual flow rights. This outcome follows since the central manager finalizes all trades and permit holders exchange rights through the common pool.

We next examine the implications of equation(12). The shadow price θ_{ik} on the bid upper bound constraint (7) identifies the increase in economic benefit if firm i were able to acquire one more consumptive use right. The bid at tranche k for firm i will be fully accepted if the following holds:

$$\theta_{ik} = P_{ik}^{b} - \pi_i \qquad (16)$$

$$(k = 1, \dots, k)$$

$$(i = 1, \dots, I)$$

The shadow price ϕ_{ik} associated with the lower bound constraint (8) is the loss in economic benefit if one additional consumptive use right is accepted at that bid (Prabodanie, et al., 2011). Thus no bids are accepted if

$$\phi_{ik} = \pi_i - P_{ik}^b > 0. \tag{17}$$

$$(k = 1, \ldots, K)$$

$$(i = 1, \ldots, I)$$

The π_i in equation (17) is the market-clearing price consumptive use price for firm i and P_{ik}^b is the marginal benefit of the consumptive use right of firm i accepting the bid. Equation (17) suggests that the marginal benefit of an additional consumptive use right is lower than the marginal cost of acquiring the right. Bids are accepted on the marginal tranche if P_{ik}^b and π_i are equal. In this case, it follows that

$$\theta_{ik} = \phi_{ik} \tag{18}$$

$$(k = 1, \ldots, K)$$

$$(i = 1, \ldots, I)$$

Initial Consumptive Use Permit Distributions and Market Settlements

In the smart market model presented in the previous section, we assumed all market participants bid their full demand functions for consumptive use rights as if they were only purchasing consumptive use rights. The initial allocation of consumptive use rights is ignored in the gross pool smart market formulation computational exercise. Once the optimal solution is found, net trades are calculated on basis of the initial allocation of consumptive use permits each market participant holds at the time of the bidding process. As noted in the previous section, market participants pay marginal cost prices (instead of price-as-bid), which are constructed on the basis of shadow prices taken from the model solution. In our model, the prices will include the marginal opportunity cost that each permit holder imposes on downstream permits when the permit holder's consumptive use contributes to binding flow constraints. This conforms to the idea in Griffin and Hsu (1993) except that they made a notable distinction between consumptive use rights and diversionary rights.

Let π_i^* denote the marginal opportunity cost price for a consumptive use permit for permit holder i. Let s_i^* represent the optimal number of consumptive use permits for firm i when the smart market model is solved and let $\hat{s}_i$ be the initial allocation of consumptive use rights for firm i. If $s_i^* > \hat{s}_i$, firm i is a net purchaser of consumptive use rights. The payment due from firm i for the purchase of consumptive use rights is

$$\Gamma_i = \pi_i^*(s_i^* - \hat{s}_i) \tag{19}$$

If $s_i^* < \hat{s}_i$, firm i is a net seller of consumptive use rights. The payment due to the firm i is

$$\Gamma_i = (\hat{s}_i - s_i^*) \tag{20}$$

If $s_i^* = \hat{s}_i$, firm i is neither buying nor selling consumptive use rights.

Smart Market Model for Consumptive and Instream Flow Rights

We next extend the previous smart market model structure to include instream flows and the corresponding demand for instream flows. The instream flow specifications follow closely those found in Anderson and Johnson (1986).

We begin by recognizing that the concern for preserving instream flows is typically focused on large sections of a river where recreational activities are often carried out along large sections of a particular stretch of a river. These observations suggest the demand for instream flows exist at various points along a river.

Let F_i denote instream flow immediately below diversion point i where diversion and consumptive use take place. We assume as previously that return flows are immediate and occur at the point of diversion. Also let the demand function for instream flows at each diversion point i be denoted as $D_i(F_i\,)$. Following Anderson and Johnson (1986), we assume the demand functions for instream flows at each diversion are the same. This demand function is denoted as $D(F_i)$. We further assume that this is a compensated demand function that can be estimated using one of the standard techniques for estimating the marginal willingness to pay for a good with public good characteristics (Anderson and Johnson, 1986; Loehman and Loomis, 2008).

To reflect the presence of instream flows the first-order equation (1) can be rewritten as:

$$V_{i+1} - V_i = -(1 - R_i)Y_i - F_i \tag{21}$$

We can use equation (2) to rewrite equation (21) for any diversion point i as follows:

$$V_i = V_0 - \sum_{j=1}^{i-1} \left(s_j + F_j\right) \tag{22}$$

The extended version of the smart market model which includes instream flow rights is presented in the following paragraphs. The additional notation for the extended version of the smart market model is presented first. We assume that the bid functions for instream flow permits are represented by discrete functions where each steep is a tranche. The index for each instream flow permit bid tranche is denoted as n $(n = 1, \dots, N)$. Let B_{in} represent the size (quantity of instream flow rights of the bid tranche $n$submitted for bid. LetD_n^b represent the price specified in bid tranche i and F_{in}^b the number of instream flow rights accepted from bid tranche n by bidder i.

The formal structure of the revised smart market model with both consumptive use and instream flow water rights is presented as follows:

$$Max\ R = \sum_{i=1}^{I} \sum_{k=1}^{K} P_{ik}^b s_{ik}^b + \sum_{i=1}^{I} \sum_{n=1}^{N} D_n^b F_{in}^b \tag{23}$$

Subject to

$$\sum_{k=1}^{K} s_{ik}^{b} = s_i \qquad (\pi_i)(24)$$

$$(i = 1, \dots, I)$$

$$s_{ik}^{b} \leq B_{ik} \qquad (\theta_{ik})(25)$$

$$(k = 1, \dots, K)$$
$$(i = 1, \dots, I)$$

$$-s_{ik}^{b} \leq 0 \qquad (\phi_{ik})(26)$$

$$(k = 1, \dots, K)$$
$$(i = 1, \dots, I)$$

$$\sum_{n=1}^{N} F_{in}^{b} = F_i \qquad (\psi_i)(27)$$

$$(i = 1, \dots, I)$$

$$F_{in}^{b} \leq B_{in} \qquad (\varepsilon_{in})(28)$$

$$(n = 1, \dots, N)$$
$$(i = 1, \dots, I)$$

$$-F_{in}^{b} \leq 0 \qquad (\mu_{in})(29)$$
$$(n = 1, \dots, N)$$
$$(i = 1, \dots, I)$$

$$\sum_{i=1}^{I} s_i + \sum_{i=1}^{I} F_i \leq \bar{s} \qquad (\pi)(30)$$

$$\frac{s_1}{(1 - R_1)} + F_1 \leq V_0 \qquad (\lambda_1)(31)$$

$$\frac{s_i}{(1 - R_i)} + F_i \leq V_0 - \sum_{j=1}^{i-1} \left(s_j + F_j\right) \qquad (\lambda_i)(32)$$

$$(i = 2, \dots I)$$

$$\tilde{V} \leq V_0 - \sum_{i=1}^{I}(s_i + F_i) \qquad (\sigma)(33)$$

The variables in parentheses of equations $(24) - (33)$ are Lagrangean multipliers.

The portions of the smart market model that pertain to the consumptive use permits remain the same as previously. We will confine our discussions to the portions of the extended model that include the instream flow permit specifications. First, the model's objective function equation (23) represents the net benefits from trading both consumptive use permits and instream flow permits. The second set of terms in equation (23) shows the net benefits that accrue from trading the instream flow permits. As stated previously, the mathematical programming model is formulated as a gross pool market and the market equilibrium for this model is independent of the initial distribution of permits (Prabodanie, et al., 2011). In this situation, the mathematical programming model is solved, the optimal quantities of consumptive use rights and instream flow rights are calculated for each participant.

The coefficient D_n^b in the second set of terms in equation (23) shows how much each block of instream flow rights is worth to an individual bidder. Equation (27) is an allocation constraint that indicates the quantity of instream flow rights accepted and the final rights position for a bidder. Constraint (28) imposes an upper bound on each bid tranche making sure that the quantity of instream flow rights does not exceed the maximum specified by the bidder. Constraint (29) requires that the number of instream flow rights in each bid tranche was positive. Constraint (30) requires that the total number of consumptive use rights and instream flow rights cannot exceed the total number of rights issued by the central market manager. Constraints $(31) - (33)$ are flow constraints that have been adjusted for the instream flow rights. The previous descriptions of these constraints apply to the extended version of the smart market as well.

Water Permit Prices for Consumptive and Instream Flow Rights

The smart market prices for consumptive use rights and instream flow rights can be found from the first order necessary conditions for the smart market model. The derivation of these first order conditions are shown in Appendix B. The relevant conditions for setting the prices are the following:

$$P_{ik}^{b} - \pi_i - \theta_{ik} + \phi_{ik} = 0 \qquad (35)$$

$$(k = 1, \dots, K)$$
$$(i = 1, , \dots, I)$$

$$\pi_i = \pi + \frac{\lambda_i}{(1 - R_i)} + \sum_{j=i+1}^{I} \lambda_j + \sigma \qquad (36)$$

$$(i = 1, \dots, I)$$

$$D_n^b - \psi_i - \varepsilon_{in} + \mu_{in} = 0 \qquad (37)$$

$$(n = 1, \dots, N)$$
$$(i = 1, \dots, I)$$

$$\psi_i = \pi + \sum_{j=i+1}^{I} \lambda_j + \sigma \qquad (38)$$

$$(i = 1, \dots, I)$$

We begin by assuming that the flow constrains are nonbinding, but constraint (30) which limits the total number permits that are available is binding. We can conclude that

$$\pi_i = \pi \qquad (39a)$$

$$\psi_i = \pi \qquad (39b)$$

$$\pi_i = \psi_i \qquad (39c)$$

for all i $(i = 1, \ldots, I)$. The shadow price π indicates the increase in net benefits of consumptive use rights or instream flow rights if the market manager increases the number of permits $\bar{s}$ by one unit. We can interpret this shadow price as the market-clearing price for consumptive use permits and instream flow permits. In this case, all consumptive use right holders and all instream flow right holders pay the same price for each water right permit traded, regardless of the type of the right. We assume that constraint (30) is binding for all of our remaining discussions.

Let us next assume that all of the flow constraints at all i diversion points as well as the flow constraint at the water course constraint (30) are binding. The pricing rule for consumptive permits is represented by equation (36) and the pricing rule for instream flow permits is given by equation (38). The interpretations for the consumptive use right price equation (36) is similar to those provided for equation (15) and will therefore not be discussed here.

We now turn our attention to the pricing rule for instream flow rights represented by equation (38). If the flow constraints are binding (this includes the constraint (33) at the end of the river course), then the holder of an instream flow permit pays a multipart price as shown in equation (38). The first term π is the market-clearing price for consumptive use permits and instream flow permits. The second set of terms represent the marginal opportunity cost that the instream flow right holder imposes on the downstream consumptive use right and instream flow right holders j when the instream flow right is held in reserve at location i.Notice in this case that the nonzero λ_j for the $j, (j = i + 1, \ldots, I)$means that the possible third-party impacts imposed on downstream right holders associated with voluntary instream flow permit trades are internalized in the marginal opportunity cost price paid by each of the permit traders. Once again, the shadow priceσ is the marginal opportunity cost of a binding flow constraint at the end of the water course.

The shadow price with the allocation constraint (27) shows the increase in the objective function equation (23) if an instream flow rights holder receives one additional instream flow right. Each instream flow permits holder pays the value ψ_i for each instream flow right and we also expect each instream flow right holder to pay or receive a different price. This outcome follows because the central manager finalizes all trades and permit holders exchange rights through the common pool.

An important conclusion follow from the results noted above. Colby (1996) has noted that heterogeneity in private values is the source of willingness of those needing additional water to bid supplies away from current right holders. Though such an allocation raises the overall economic benefit, it still imposes externalities on certain rights holders. By letting the marginal opportunity cost price paid or received by each of the permit holders determine the optimal quantity to be traded, the model internalizes such externalities to a great extent. This price may not incorporate all such costs due the spatial-temporal variability of such externalities. Yet since the optimal prices and quantities are determined at each tranche over time (or at discrete intervals), these external effects are minimized.

We now examine equations (35) and (37). First, equation (35) is concerned with consumptive use permits and the interpretation of its components is the same as for equation (12). We refer the reader to the corresponding discussions for equations$(16) - (18)$.

The shadow price ε_{in} on the bid constraint (28) shows the increase in economic benefit if the ith instream flow right holder were to acquire one more instream flow right. The bid tranche n for the ith instream flow right holder is fully accepted if

$$\varepsilon_{in} = D_n^b - \psi_i \qquad (40)$$

$$(n = 1, \dots, N)$$

$$(i = 1, \dots, I)$$

The shadow price μ_{in} associated with the lower bound constraint (29) is the loss in economic benefit if one additional instream flow right is accepted at that bid. No bids are accepted if

$$\mu_{in} = \psi_i - D_n^b > 0 \qquad (41)$$

$$(n = 1, \dots, N)$$

$$(i = 1, \dots, I)$$

The price ψ_i is the marginal cost price for instream flow permit holder i and D_n^b is the marginal benefit of the instream flow right of the ithholder accepting the bid. We conclude from equation (41) that the marginal benefit of additional instream flow right is less than the marginal cost of acquiring that particular instream flow right. Bids are accepted on the marginal tranche if

$$\varepsilon_{in} = \mu_{in} \qquad (42)$$

$$(n = 1, \dots, N)$$
$$(i = 1, \dots, I)$$

This of course means that D_n^b is equal to ψ_i.

Initial Consumptive Use and Instream Flow Permit Distributions and Market Settlements

The earlier section concerning the initial permit distributions and market settlements pertained only to consumptive use permit trading. However, much of the discussion in that section is relevant when the permit market is set for both consumptive use and instream flow permit trades. Thus none of the discussions is repeated here. We will instead focus on the market settlements when both types of permits are traded.

Let π_i^* be the optimal marginal opportunity cost price for a consumptive use permit and ψ_i^* the optimal marginal opportunity cost price for an instream flow permit at location i. Let s_i^* and F_i^* represent the optimal number of each type of water right permit at the ith location. Also let $\hat{s}_i$ and $\hat{F}_i$ represent the initial allocation of each type of permit at location i. If $s_i^* > \hat{s}_i$and

$F_i^* > \hat{F}_i$, the rights holders at location i are net purchasers of water rights permits. The payment due for each type of permit at location i is

$$\Gamma_i = \pi_i^*(s_i^* - \hat{s}_i) \tag{43}$$

and

$$\Omega_i = \psi_i^*\left(F_i^* - \hat{F}_i\right) \tag{44}$$

If $s_i^* < \hat{s}_i$and $F_i^* < \hat{F}_i$, the rights holders are net sellers at location i. The payments due in this case are

$$\Gamma_i = \pi_i^*(\hat{s}_i - s_i^*) \tag{45}$$

and

$$\Omega_i = \psi_i^*\left(\hat{F}_i - F_i^*\right) \tag{46}$$

If $s_i^* = \hat{s}_i$and $F_i^* = \hat{F}_i$, no trades take place at location i.

Conclusions and Policy Implications

The above discussion on permit trading with and without instream flow rights throws significant directions for water allocation and pricing rules when flow constraints are binding. The results show that the marginal opportunity cost or the shadow prices from the model solutions internalize the third party externalities in both cases. As evident from equation (38), the price when instream flow rights are binding accounts for instream rights apart from consumptive use rights. This multipart pricing at each bid tranche though analytically cumbersome, the application of linear programming for recovering the shadow price increases the tractability of the actual solution. On the other hand, when the flow constraints are not binding at any point of diversion, the price paid by each trader is uniform in both cases. Obviously this is rarely encountered in practice especially when dealing with instream flows as a public good.

Studies have shown that surface water transfers on the basis of consumptive use water rights will not lead to the third-party impairment as long as none of the upstream flow constraints are binding and the water rights are treated as private property rights. However, a simple transfer of water rights at any point of diversion, will violate preexisting rights of others (third party externalities) when the flow constraints are binding and surface water possesses public good characteristics. Thus questions have been raised about the efficiency of markets or bilateral transfers in presence of instream flow rights and the high transaction costs they sometimes entail. This paper proposes an alternative institutional arrangement called smart markets which maximize the aggregate gains from trading by allowing trades to be consummated through a common pool.

There are three aspects of trading from a common pool that is apparent from the model results highlighted in this paper. First, since transactions occur through a centralized market manager who decides upon the optimal prices and the quantities to be traded, this model minimizes the transaction costs of trade—in other words, it maximizes the efficiency gains from trading. Second, even when the consumptive use rights are considered to be a private good, the shadow prices evolving from the centralized solution, incorporates the third party external costs imposed by any trader. Thus the financial burden of compensating victims who are affected by lower flows downstream or insufficient availability of water for diversions, are avoided. Finally, it shows that the prices paid or received for an amount of instream flow rights will differ since it is decided by an optimization problem solved by the market manager, given the bids and offers at any point in time. Thus unlike in a bilateral setting, prices are not matched up at every period of time.

The implications of these are manifold. By encouraging trades through a common pool, such an institutional arrangement raises the economic and socio political feasibility of trading in instream rights since it minimizes transaction costs and strategic behavior by water holders. This is particularly important for transboundary water management problems where efficient allocation of water rights (diversionary or consumptive use rights) are often impeded by myriad institutional laws governing water transfers from state to state or from nation to nation. Second, by allowing trade in consumptive water rights, it imposes minimum third party spatial externalities even if we assume heterogeneous users along the river. Trading on the basis of consumptive use narrows down the difference between the private and public good aspects of water rights, in presence of instream flows. Finally, by ensuring that the initial allocation of rights matter only after the optimal prices and quantities have been solved, such a system increases the gains in economic efficiency since any participant pays the price that includes the full opportunity cost imposed on downstream rights holders.

While the conflict between private water rights and instream flows remain a highly debated topic in the economic literature, this type of smart market arrangement offers a middle ground between the first best Pareto efficient outcomes and outcomes with institutional burdens and high transaction costs. It does rest on some simplifying assumptions like homogenous demand functions for all users claiming instream flow rights. Also uncertainties in return flows and information asymmetries may affect model results. Yet at a juncture when water allocation across several parties and involving states and nations are swamped by rigorous institutional and political impairments and when large scale water markets are criticized for the lack of fairness and equality in distribution of resources, this simple arrangement can provide intertemporal solution to water allocation problems in situations dominated by third party externalities and transaction costs.

References

Alvey, T., D. Goodwin, M. Xingwang, D. Streeffert, and D. Sun. 1998."A Security-Constrained Bid-Clearing System for the New Zealand Wholesale Electricity Market." *IEEE Transactions on Power Systems*, 13: 340-346.

Anderson, T.L., and R.N. Johnson. 1986. "The Problem of Instream Flows." *Economic Inquiry*, 24: 535-554.

Ando, A.W., and D. Ramirez-Harrington. 2006. "Tradable Discharge Permits: A Student Friendly Game." *Journal of Economic Education*, 37: 187-201.

Becker, N. 1995. "Value of Moving from Central Planning to a Market System: Lessons from the Israeli Water Sector." *Agricultural Economics*, 12: 11-21.

Gisser, M., and R.N. Johnson. 1983. "Institutional Restrictions on the Transfer of Water Rights and the Survival of an Agency." In *Water Rights: Scarce Resource Allocation, Bureaucracy, and the Environment*, T.L. Anderson, ed. Ballenger Publishing Company, Cambridge, MA, pp. 137-165.

Howitt, R. and K. Hansen. 2005. "The Evolving Western Water Markets." *Choices*, 20: 59-63.

Johnson, R.N., M. Gisser, and M. Werner. 1981. "The Definition of a Surface Water Right and Transferability." *Journal of Law and Economics*, 24: 273-288.

Loehman, E., and J. Loomis. 2008. "In-Stream Flow as a Public Good: Possibilities for Economic Organization and Voluntary Local Provision." *Review of Agricultural Economics*, 30: 445-456.

Livingston, M., and T.A. Miller. 1986. "A Framework for Analyzing the Impact of Western Instream Flows on Choice Domains: Transferability, Externalities, and Consumptive Use." *Land Economics*, 62: 269-277.

McCabe, K.A., S.J. Rassenti, and V.L. Smith. 1991. "Smart Computer-Assisted Markets." *Science*, 245: 534-538.

Montgomery, J.W. 1972. "Markets in Licenses and Efficient Pollution Control Programs."*Journal of Economic Theory*, 5:395-418.

Murphy, J.J., A. Dinar, R.E. Howitt, E. Mastrangelo, S.J. Rassenti, and V.L. Smith. 2006. "Mechanisms for Addressing Third Party Impacts from Voluntary Water Transfers." In *Using Experimental Methods in Environmental and Resource Economics*, J. List (ed.). Elgar, 91-112.

Murphy, J.J., A. Dinar, R.E. Howitt, S.J. Rassenti, and V.L. Smith. 2000. "The Design of 'Smart' Water Market Institutions Using Laboratory Experiments." *Environmental and Resource Economics*, 17: 375-494.

Murphy, J.J., A. Dinar, R.E. Howitt, S.J. Rassenti, V.L. Smith, and M. Weinberg. 2009. “The Design of Water Markets When Instream Flows Have Value.” *Journal of Environmental Management,* 90: 1089-1096.

Pinto, A.A., Raffensperger, J.F., Cochrane, and Read, E.G. 2013. “Proposed Smart Market Design for Sediment Discharge.” *Journal of Water Resources Planning and Management*, 139: 96-108.

Prabodanie, R.A.R., J.F. Raffensperger, E.G. Read, and M.W. Milke. 2011. LP Models for Pricing Diffuse Nitrate Discharge Permits.” *Annals of Operations Research,* DOI 10.1007/s10r79-011-0941-0.

Raffensperger, J.F. 2009.“Net Pool versus Gross Pool Formulations.” Canterbury University.

Rose, M. 1973.“Market Problems in the Distribution of Emission Rights.”*Water Resources Research,* 9, 1132-1144.

Weber, M. 2001. “Markets for Water rights under Environmental Constraints.”*Journal of Environmental Economics and Management,* 42: 53-64.

Willett, K., A, Caplanova, and R. Sivak. 2013. “Pricing Mechanisms for Cap and Trade Policies: Computer Assisted-Smart Markets for Air Quality,” *Journal of Environmental Planning and Management,* forthcoming.

Zeitouni, N., N. Becker, and M. Shechter.1994. “Models of Water Market Mechanisms and an Illustrative Application to the Middle East.” *Resource and Energy Economics*, 16: 303-319.

Appendix A

Lagrangean Function and First Order Conditions

$$\mathcal{L} = \sum_{l=1}^{I}\sum_{k=1}^{K} P_{ik}^{b} s_{ik}^{b} - \sum_{i=1}^{I}\pi_i\left(\sum_{k=1}^{K} s_{ik}^{b} - s_i\right) - \pi\left(\sum_{i=1}^{I} s_i - \bar{s}\right) - \sum_{i=1}^{I}\sum_{k=1}^{K}\theta_{ik}\left(s_{ik}^{b} - B_{ik}\right) - \sum_{i=1}^{I}\sum_{k=1}^{K}(-s_{ik}) \text{-} -\lambda_1\left[\frac{s_1}{(1-R_1)} - V_0\right] - \sum_{i=2}^{I}\lambda_i\left[\frac{s_i}{(1-R_i)} - V_0 + \sum_{j=1}^{i-1} s_j\right] - \sigma\left[\bar{V} - V_0 + \sum_{i=1}^{I} s_i\right] \qquad (A.1)$$

$$\frac{\partial\mathcal{L}}{\partial s_{ik}^{b}} = P_{ik}^{b} - \pi_i - \theta_{ik} + \phi_{ik} \leq 0 \qquad (A.2a)$$

$$\frac{\partial\mathcal{L}}{\partial s_{ik}^{b}} s_{ik}^{b} = 0 \qquad (A.2b)$$

$$(k = 1, \dots, K)$$
$$(i = 1, \dots I)$$

$$\frac{\partial\mathcal{L}}{\partial s_i} = \pi_i - \pi - \frac{\lambda_i}{(1-R_i)} - \sum_{j=i+1}^{I}\lambda_j - \sigma \leq 0 \qquad (A.3a)$$

$$\frac{\partial\mathcal{L}}{\partial s_i} s_i = 0 \qquad (A.3b)$$

$$(i = 1, \dots, I)$$

$$P_{ik}^{b} - \pi_i - \theta_{ik} + \phi_{ik} = 0 \qquad (A.4)$$

$$(k = 1, \dots, K)$$
$$(i = 1, \dots, I)$$

$$\pi_i = \pi + \frac{\lambda_i}{(1-R_i)} + \sum_{j=i+1}^{I}\lambda_j + \sigma = 0 \qquad (A.5)$$

Appendix B

$$
\begin{aligned}
\mathcal{L} = \sum_{i=1}^{I}\sum_{k-1}^{K} P_{ik}^{b}\, s_{ik}^{b} \\
&+ \sum_{i=1}^{I}\sum_{n=1}^{N} D_n^b F_{in}^b - \sum_{i=1}^{I} \pi_i \left(\sum_{k=1}^{K} s_{ik}^b - s_i\right) \\
&- \sum_{i=1}^{I}\sum_{k=1}^{K} \theta_{ik}\left(s_{ik}^b - B_{ik}\right) \\
&- \sum_{i=1}^{I}\sum_{k=1}^{K} \phi_{ik}\left(-s_{ik}^b\right) \\
&- \sum_{i=1}^{I} \psi_i \left(\sum_{n=1}^{N} F_{in}^b - F_i\right) \\
&- \sum_{i=1}^{I}\sum_{n=1}^{N} \varepsilon_{in}\left(F_{in}^b - B_{in}\right) \\
&- \sum_{i=1}^{I}\sum_{n=1}^{N} \mu_{in}\left(-F_{in}^b\right) - \pi\left(\sum_{i=1}^{I} s_i + \sum_{i=1}^{I} F_i - \bar{s}\right) \\
&- \lambda_1\left[\frac{s_1}{(1-R_1)} + F_1 - V_0\right] \\
&- \sum_{i=2}^{I} \lambda_i \left[\frac{s_i}{(1-R_i)} + F_i + \sum_{j=1}^{i-1}\left(s_j + F_i\right) - V_0\right] \\
&- \sigma\left[\tilde{V} - V_0 + \sum_{i=1}^{I}(s_i + F_i)\right]
\end{aligned}
\qquad (B.1)
$$

$$\frac{\partial \mathcal{L}}{\partial s_{ik}^b} = P_{ik}^b - \pi_i - \theta_{ik} + \phi_{ik} \le 0 \qquad (B.2a)$$

$$\frac{\partial \mathcal{L}}{\partial s_{ik}} s_{ik} = 0 \qquad (B.2b)$$

$$(k = 1, \dots, K)$$
$$(i = 1, , \dots, I)$$

$$\frac{\partial \mathcal{L}}{\partial s_i} = \pi_i - \pi - \frac{\lambda_i}{(1-R_i)} - \sum_{j=i+1}^{I} \lambda_j - \sigma \le 0 \qquad (B.3a)$$

$$\frac{\partial \mathcal{L}}{\partial s_i} s_i = 0 \tag{B.3b}$$

$$(i = 1, \dots, I)$$

$$\frac{\partial \mathcal{L}}{\partial F_{in}^b} = D_n^b - \psi_i - \varepsilon_{in} + \mu_{in} \leq 0 \tag{B.4a}$$

$$\frac{\partial \mathcal{L}}{\partial F_{in}^b} F_{in}^b = 0 \tag{B.4b}$$

$$(n = 1, \dots, N)$$

$$(i = 1, \dots, I)$$

$$\frac{\partial \mathcal{L}}{\partial F_i} = \psi_i - \pi - \sum_{j=i+1}^{J} \lambda_j - \sigma \leq 0 \tag{B.5a}$$

$$\frac{\partial \mathcal{L}}{\partial F_i} F_i = 0 \tag{B.5b}$$

$$(i = 1, \dots, I)$$