IRRIGATION TECHNOLOGY ADOPTION AND GAINS FROM WATER TRADING UNDER ASYMMETRIC INFORMATION

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Abstract: We develop a water allocation and irrigation technology adoption model under the prior appropriation doctrine with asymmetric information among heterogeneous farmers and between farmers and water authorities; farmers' heterogeneity is defined by a mix of land quality and knowledge. We find that adverse selection reduces the adoption of modern irrigation technology. We also show that even with asymmetric information, incentives for water trade exist and lead to additional technology adoption with gains to all parties. This suggests that under asymmetric information, a thin secondary market improves the allocation of water resources and induces additional adoption of modern irrigation technologies.

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Irrigation Technology Adoption and Gains from Water Trading Under Asymmetric Information

In several regions in the US, the prior appropriation doctrine is used to allocate water. Under this doctrine, priority of right is determined according to the "first in time, first in right" rule and senior water users can take as much water as they can beneficially use. Such systems result in nonmarginal pricing of water that does not reflect the scarcity value of water. This together with a "use it or lose it" rule on water under which water rights cannot be transferred or sold lead to inefficiency in the allocation of water across users (Burness and Quirk) and reduced incentives to conserve water in times of scarcity or to adopt efficient irrigation technologies (Zilberman, MacDougall and Shah).

To reduce the inefficiencies inherent in such a system, some states, e.g., Oregon, Idaho, Colorado, and Utah, are assigning water quotas and a water fee depending on intended use, seniority of water right, and availability of resources.[1] The U.S. Bureau of Reclamation recommends setting water rates that would lead to efficient use of water but acknowledges the difficulties that arise from "gathering the technical details to support the design and administration of workable rate schedules."(p.12). Other states, or at least California in 1991, are moving towards water markets in order to increase efficiency of water use (Howitt). Asymmetric information about heterogeneous land qualities and values attached to water between users and the water agency can distort the determination of water quotas and fees under the prior appropriation doctrine; it can also impede the allocation of property rights to water and water trades that would achieve efficient water use. Additionally, transactions costs and an inadequate numbers of willing buyers and sellers within geographic areas limited by constraints in transporting water could also cause markets for water to fail to achieve efficiency (Freyfogle; Livingston, 1993).

The purpose of this article is twofold. First, we seek to examine the impact of asymmetric information on the regulator's decision problem of assigning water quotas among farmers while taking into account their prior appropriation rights. In the absence of complete information about heterogeneous farmer's types, defined by their land quality, which influences their irrigation technology choice and water use, we examine the design of an incentive mechanism by which the regulator assigns quotas and sets a fee for water use. We examine its implications for modern irrigation technologies adoption and water use as compared to those under full information. We do this by applying the general mechanism design framework in Laffont and Tirole to determine water quotas and fees under asymmetric information. We then extend that framework to analyze the gains from water trading under asymmetric information. Due to transportation constraints, trading typically has to be confined geographically and would most likely be among a few water users. We therefore focus on bilateral water trades through an independent broker and analyze its implications for additional technology adoption and social welfare.[2]

Our article differs from the existing literature on irrigation technology adoption and water markets in several ways. Caswell and Zilberman analyze technology adoption decisions under perfect information with no constraint on water availability. Smith and Tsur address the design of incentive compatible mechanisms for water pricing under asymmetric information but focus on riparian rights. Neither study considers water trading. In the absence of water trading, senior water right holders have the incentive to irrigate all their land, which leaves the junior right holder with little or no water (Burness and Quirk) and to keep using traditional irrigation technologies (Shah, Zilberman and Chakravorty). Carey and Zilberman extend this to analyze the implications of water markets for irrigation technology choice under uncertainty about water availability and price while Dinar and Letey analyze the implications of water markets for drainage reduction. The above studies ignore an important aspect of the problem, namely the inefficiencies in water use and pricing introduced by asymmetric information and its implications for the efficiency of water markets.

Our results show that under asymmetric information the optimal water quotas for the senior right holders are smaller than under full information, therefore leaving more water for junior right holders. However, the optimal incentive mechanism imposes lower water fees under asymmetric information than under full information, particularly on the high quality senior right holders who use the traditional irrigation technology. Together this leads to less adoption of modern irrigation technology under asymmetric information than under full information. Furthermore, we find that under conditions of adverse selection, a secondary water-trading phase or "second market" should be considered in order to improve water allocation. We show that even under asymmetric information, bilateral water trading can increase social efficiency of water allocation and leads to more modern irrigation technology adoption than the non-trading situation without inducing further budgetary strain on the regulator. In the next section, we present our theoretical framework and a benchmark model where water quotas are determined under full information and are not transferable. We then introduce asymmetric information, examine its implications in the absence of water trading, and then examine the gains from water trading. A numerical simulation provides more insights and is followed by a concluding section.

Theoretical Framework

We consider *N* farmers, indexed by *i*=1,…,*N* producing the same crop, using water and irrigation technologies as inputs, and facing an exogenous output price *P*. Farmers are heterogeneous in their type, e.g., land quality and skills, denoted by θ_i. Farmer types are assumed to be independently distributed from each other with density $f(\theta_i)$ and a cumulative distribution $F(\theta_i)$ over the support $[\underline{\theta}, \overline{\theta}]$.

The Irrigation Technology

Farmers have a choice of two alternative irrigation technologies, $t \in \{L, H\}$ where *L* is the traditional technology such as furrow irrigation, and *H* is the modern technology such as sprinkler or drip. These technologies differ in the effectiveness with which they enable the effective uptake of applied irrigation water by crops. Applied water per acre is denoted by w_i^t. The portion of this water effectively consumed by crops depends on land quality and irrigation technology. We assume a linear relation between effective water use e_i^t and applied water with a multiplicative quality-augmenting function

$e_i^t = h_i^t(\theta_i) w_i^t$, where $h_i^t(\theta_i)$ is the irrigation effectiveness of technology *t* for farmer *i*. The function h^t is the percentage of water absorbed or used effectively by the crop, hence it takes values from 0 to 1. We assume that $h_i^t(.)$ is non-decreasing with $h_i^H(\theta_i) \geq h_i^L(\theta_i)$ and is concave with $h_i^H(\overline{\theta}) = 1$. We distinguish between the parameter of land quality or agents' types, $\theta_i \in [\underline{\theta}, \overline{\theta}]$, and the effectiveness of irrigation technology that we define as $h_i^t(\theta_i) = \left(\frac{\theta_i - \underline{\theta}}{\overline{\theta} - \underline{\theta}} \right)^{\alpha_i}$. When the traditional technology is in use $\alpha_i = 1$ and when the modern technology is in use $\alpha_i \in]0,1[$. The per-acre fixed cost of the traditional technology is $c^L = 0$, while that of the modern technology is $c^H > 0$.

The Production Function

Output per acre is denoted by y_i^t and is assumed to be a function of the quantity of effective water used by farmer *i* when technology *t* is adopted. Caswell and Zilberman define the elasticity of marginal productivity of effective water as $emp_i^t = -e_i^t \frac{\partial^2 y / \partial e_i^{t^2}}{\partial y / \partial e_i^t}$ and show that the optimal quantity of applied water decreases with respect to farmer's type when $emp_i^t > 1$. To keep our analysis tractable, while allowing for $emp_i^t > 1$ we assume that the production function is quadratic, as in Caswell, Lichtenberg, and Zilberman, and Khanna, Isik, and Zilberman. The constant returns to scale production function for farmer *i* is represented by

$y_i\left(w_i^t, h^t(\theta_i)\right) = \max\left\{-d + b\left(w_i^t\ h^t(\theta_i)\right) - a\left(w_i^t\ h^t(\theta_i)\right)^2, 0\right\}$, where y_i is yield per acre, $a > 0, b > 0,$ and $d \geq 0$ are constants.

Profit Maximization and Irrigation Technology Choice

For every unit of water, there is a private cost *k* of diverting it from its source to the field. With g being the per-unit cost of water, the per-acre profit (in dollars) for farmer *i* under technology *t* is thus defined by:

(1) $$\pi_i^t\left(w_i^t, h_i^t(\theta_i)\right) = Py_i\left(w_i^t, h_i^t(\theta_i)\right) - kw_i^t - gw_i^t - c^t,$$

where *P* is the price per unit yield.

The profit maximization problem is analyzed in two stages; in the first stage, the water input is determined given a technology *t* then in the second stage, the farmer selects the technology that yields the highest profit. When $\theta_i = \underline{\theta}$ yield and profits with either technology would be zero and neither technology will be adopted. When $\theta_i = \overline{\theta}$, both technologies will be equally efficient and there will be no water use savings with the adoption of the modern technology. Given fixed adoption costs of c^H, Caswell, Zilberman, and Casterline show that the profit differential (net of the fixed costs of adoption) declines as θ increases. Given the assumptions that $h_i^H\left(\theta_i\right)$ is concave and $emp_i^t > 1$, they also show that there is a single crossing point between π_i^L and π_i^H. For $\theta_i \in \left[\underline{\theta}, \theta^s\right]$, where θ^s solves $\pi_i^H(\theta^S) = \pi_i^L(\theta^S)$ such that $\pi_i^t > 0, \forall t \in \{L, H\}$, farmers adopt the modern technology (*t*=*H*) since $\pi_i^H \geq \pi_i^L$ and $\pi_i^H \geq 0$. For $\theta_i \in \left[\theta^s, \overline{\theta}\right]$ the traditional technology is selected (t=L). Therefore, the proportion of farmers adopting the modern irrigation technology is $F\left(\theta^{s}\right)$.

The total quantity of water available to farmers in the region is assumed to be fixed at $\overline{w}$; farmers divert water according to the priority set when they apply for water rights. We assume that water is allocated according to the modified prior appropriation scheme whereby farmers are ranked according to seniority, $i=1,...,N$, with farmer 1 being the most senior and N the most junior. Furthermore, we assume that farmers with senior water rights are always allocated enough water to at least break even but that some junior right holders may be left without water.

Model Assumptions

We assume an interior solution for water demand, i.e. $w_i^t \le \frac{b}{2ah_i^t(\theta_i)}$ for all $\theta_i \in \left[\underline{\theta},\overline{\theta}\right]$, and that total demand exceeds supply. We also assume that $emp_i^t > 1$, implying that $w_i^t > \frac{b}{4ah_i^t(\theta_i)}$ for all i and t and water use decreases with respect to the farmer's type, $\frac{dw_i^t\left(\theta_i\right)}{d\theta_i} < 0$. Efficient water allocation must then lie between $\frac{b}{4ah_i^t(\theta_i)}$ and $\frac{b}{2ah_i^t(\theta_i)}$.

Water Allocation under Full Information: Prior Appropriation Doctrine

Under the prior appropriation doctrine, water allocation is determined by seniority of right with farmers at the front of the queue being allowed to use as much water as they can beneficially use while junior farmers at the end of the queue receive the residual water. We now consider the problem of the regulator who seeks to determine water quotas for each farmer to maximize social benefits constrained by the seniority of rights and water availability. The regulator determines the water quota of each farmer in the queue sequentially by maximizing the social benefit generated by allocating water to that farmer. We assume that senior right holders will be granted enough water to at least break even and continue production. The social benefit does not encompass the environmental externalities due to water use.

Livingston (1998) reports the existence of water commissioners who act as "River Cops" who monitor the use of water and ensure that the established priorities and allocation levels are respected. Such activity is costly to society due to transactions costs and the social cost of raising public funds to undertake such expenditures. Additionally, there could be an environmental cost associated with the use of water. The social cost of water is therefore represented $\left(1+\lambda\right)gw_i^t$ where $0<\lambda<1$. The social gain generated by farmer *l* is therefore represented as follows:

(2) $$S_i^t\left(w_i^t,h_i^t(\theta_i)\right)=Py_i\left(w_i^t,h_i^t(\theta_i)\right)-kw_i^t-\left(1+\lambda\right)gw_i^t-c^t .$$

With $l=1,...,i-1$ being the index for all water users holding water rights senior to *i*'s, under full information, the regulator's problem is:

(3) $\max_{w_i^t} S_i^t\left(w_i^t, h_i^t(\theta_i)\right)$ s.t. $0 \le w_i^t \le \overline{w} - \sum_{l<i} w_l^t$ and $\pi_l^t\left(w_l^t, h_l^t(\theta_l)\right) \ge 0\,; \forall l < i$.

The interior solution to (3) is:

(4) $$w_i^{t*} = \frac{b}{2ah_i^t} - \frac{k + g(1+\lambda)}{2aP(h_i^t)^2} \quad \text{;for } j_* - 1 \text{ farmers.}$$

This implies that $j_* - 1$ farmers receive their social-gain-maximizing quota and that there will be at most one farmer, the j_* th, who receives a partial quota $w_{j_*}^{t*} = \overline{w} - \sum_{i=1}^{j_*-1} w_i^{t*}$. The remaining $N - j_*$ are left without water, $w_{i>j_*}^{t*} = 0$. The proportion of farmers adopting the modern irrigation technology is $F\left(\theta^*\right)$. With $\lambda > 0$, the socially optimal level of adoption will differ from the privately optimal level because the regulator takes into account the external costs of providing water, which the farmer does not.

When collecting water fees is costless (that is $\lambda = 0$), water-use is given by $w_i^{t0} = \frac{b}{2ah_i^t} - \frac{k+g}{2aP(h_i^t)^2}$. As λ increases, water quotas decrease the most for farmers with low types. If there are senior right holders that are of low type, a reduction in their water quotas makes more water available for some junior right holders that may be of higher type and use water more efficiently. Thus, a reduction in water quotas can improve the allocation of scarce water between senior right holders and junior right holder through a better risk sharing during droughts as shown by Burness and Quirk.

Water Allocation under Asymmetric Information

We now consider the case when the land quality parameter θ_i is unknown to parties other than farmer *i*. The regulator uses a direct revelation mechanism to determine water quotas and water fees, water users when applying for a water right reveal a parameter $\hat{\theta}_i$ about their characteristic; the revealed parameter is not necessarily the true parameter θ_i. The regulator's problem is to design a contract consisting of a water quota w_i^{t**} and a water fee Φ that would be incentive compatible (i.e. ensure truth-telling) and rational. This contract $\left\{w_i^{t**}(\hat{\theta}_i), \Phi\left(w_i^{t**}(\hat{\theta}_i)\right)\right\}$ is determined for every $\hat{\theta}_i$ using a revelation mechanism, as described below.

Let $\Pi\left(\hat{\theta}_i, \theta_i\right) = Py\left(w_i^t(\hat{\theta}_i), \theta_i\right) - kw_i^t(\hat{\theta}_i) - \Phi\left(w_i^t(\hat{\theta}_i)\right)$ be the profit realized by farmer *i* when his true type is θ_i and he announces $\hat{\theta}_i$. The pair $\left\{w_i^{t**}(\hat{\theta}_i), \Phi\left(w_i^{t**}(\hat{\theta}_i)\right)\right\}$ is a truth-telling mechanism if it is in the interest of each farmer to reveal his true type. To make the notation less burdensome we use a dot on top of the variable to designate the derivative of that function with respect to θ_i.

Proposition 1: A pair $\left\{w_i^t(\theta_i), \Phi\left(w_i^t(\theta_i)\right)\right\}$ constitutes an incentive compatible mechanism if for all $\theta_i \in \left[\underline{\theta}, \overline{\theta}\right]$ we have:

(5) $$\frac{\partial w_i^t(\theta_i)}{\partial \theta_i} \leq 0, \qquad \text{and}$$

(6) $$\Phi\left(w_i^t(\theta_i)\right) = P\ y_i\left(w_i^t(\theta_i), h_i^t(\theta_i)\right) - k\ w_i^t(\theta_i) - c^t - \int_{\underline{\theta}}^{\theta_i} \dot{\pi}_i^t\left(w_i^t(u), h_i^t(u)\right) du\ ,$$ where

(7) $$\dot{\pi}_i^t\left(w_i^t(u), h_i^t(u)\right) = P\ \dot{h}_i^t(u)\ w_i^t(u)\left(b - 2a\ h_i^t(u)\ w_i^t(u)\right),\ \forall u \in \left[\underline{\theta}, \theta_i\right].$$

Proof: Using the same approach as in Laffont and Tirole (p. 63), one can establish that $w_i^t(\theta_i)$ is a decreasing function of θ_i. We then use this result to determine the water fee that makes the pair $\left\{w_i^t(\theta_i), \Phi\left(w_i^t(\theta_i)\right)\right\}$ an incentive compatible contract. The first-order condition for truth telling is given by:

(8) $$\left.\frac{\partial \Pi\left(\hat{\theta}_i, \theta_i\right)}{\partial \hat{\theta}_i}\right|_{\hat{\theta}_i = \theta_i} = 0\ .$$

Expression (8) implies:

(9) $$\left[P\left(bh_i^t(\theta_i) - 2aw_i^t(\theta_i)\left(h_i^t(\theta_i)\right)^2\right) - k - \frac{\partial \Phi\left(w_i^t(\theta_i)\right)}{\partial w_i^t(\theta_i)}\right]\dot{w}_i^t(\theta_i) = 0\ .$$

If we set $\pi_i^t\left(w_i^t(\theta_i), h_i^t(\theta_i)\right) = \Pi\left(\theta_i, \theta_i\right)$, take its total derivative with respect to θ_i, and use (10) to simplify the expression we obtain:

(10) $$\dot{\pi}_i^t = P\dot{h}_i^t w_i^t\left(b - 2ah_i^t w_i^t\right).$$

We can now integrate (10) between $\underline{\theta}$ and θ_i to obtain total profits for farmer *i* with technology *t*. We then equate that to the profit expression in (1) and solve for the *ex-post* optimal water fee given by the expression in (6).

Proposition 1 establishes the relation between $w_i^t(\theta_i)$ and θ_i and the relation between the water quota $w_i^{t^{**}}(\theta_i)$ and the water fee $\Phi\left(w_i^{t^{**}}(\theta_i)\right)$. The water fee schedule in (6) imposes second-degree price discrimination, since users are offered different water quantities at different prices, but all users of the same type pay the same price for each unit of water. With asymmetric information, a water fee schedule that imposes second-degree price discrimination is necessary in order to minimize informational rent while inducing truth telling. This is in contrast to the water fee schedule used in the case of full information, where social gain can be maximized by using a simpler non-discriminative fee schedule. Any fee schedule that imposes price discrimination results only in a transfer of rents between the farmers and the regulator and does not affect aggregate social gain.

The properties of the water fee schedule under asymmetric information cannot be studied analytically because the sign of the derivatives with respect to the farmer's type cannot be determined and the derivatives with respect to water quantity cannot be obtained in a closed form due to the complexity of the integral function in (6). A computational illustration in the next section is provided for additional insights about the shape of the water fee schedule.

We now turn to the regulator's problem of determining the water quotas allocated under asymmetric information. We determine these by maximizing the social gain function for each of the *N* farmers subject to the incentive compatibility constraints (5) and (10) and the constraint that profits must be non-negative for the senior right holders. After substituting for π_i^t from (1) into (2) and rearranging we can write the social gain function for the i^{th} farmer as:

(11) $S_i^t\left(w_i^t, h_i^t(\theta_i)\right) = (1\text{-}\lambda)\left(P\left(-d + bw_i^t h_i^t(\theta_i) - a\left(w_i^t h_i^t(\theta_i)\right)^2\right) - kw_i^t - c^t\right) + \lambda\pi_i^t - gw_i^t$.

If water is available, the regulator's problem is:

(12) $\max_{w_i^t,\pi_i^t} \int_{\underline{\theta}}^{\bar{\theta}} S_i^t\left(w_i^t(\theta_i), h_i^t(\theta_i)\right) f(\theta_i) d\theta_i$ subject to (5), (10), and $\pi_i^t \geq 0$.

Following Laffont and Tirole (p. 67), we solve (12) by writing it as a Hamiltonian system with $\mu(\theta_i)$ denoting the Pontryagin multiplier and considering only constraint (10),

(13)
$$H\left(w_i^t, \pi_i^t, \mu\right) = \left((1\text{-}\lambda)\left(P\left(-d + bw_i^t h_i^t - a\left(w_i^t h_i^t\right)^2\right) - kw_i^t - c^t\right) + \lambda\pi_i^t - gw_i^t\right) f(\theta_i) + \mu(\theta_i) P\dot{h}_i^t w_i^t\left(b - 2ah_i^t w_i^t\right).$$

The first-order conditions are:

(14)
$$\frac{\partial H}{\partial w_i^t} = \left((1-\lambda)\left(P(bh_i^t - 2a(h_i^t)^2 w_i^t) - k\right) - g\right) f + \mu P\dot{h}_i^t\left(b - 4ah_i^t w_i^t\right) = 0,$$

(15)
$$-\frac{\partial H}{\partial \pi_i^t} = \dot{\mu} = -\lambda f \text{ and } \mu(\bar{\theta}) = 0,$$

(16)
$$\dot{\pi}_i^t = P\dot{h}_i^t w_i^t\left(b - 2ah_i^t w_i^t\right) \text{ and } \pi_i^t(\underline{\theta}) = 0.$$

Integrating (15) between θ_i and $\bar{\theta}$ and using its boundary condition we get $\mu(\theta_i) = \lambda\left(1 - F(\theta_i)\right)$ and with (14) we solve for the optimal quantity of water:

(17)
$$w_i^{t**} = \frac{Pb\left((1-\lambda)h_i^t + \lambda\dot{h}_i^t R(\theta_i)\right) - \left(g + k(1-\lambda)\right)}{2aPh_i^t\left((1-\lambda)h_i^t + 2\lambda\dot{h}_i^t R(\theta_i)\right)}, \text{ where } R(\theta_i) = \frac{1 - F(\theta_i)}{f(\theta_i)}.$$

The Pontryagin multiplier, $\mu(\theta)$, is the marginal contribution of $\pi_i^t(.)$ to $S_i^t(.)$ which ranges from λ to zero for all $\theta_i \in \left[\underline{\theta}, \bar{\theta}\right]$. This implies that when $\theta_i = \bar{\theta}$ the contribution of $\pi_i^t(.)$ to $S_i^t(.)$ is maximized.

In solving the model in (14) we implicitly assume that the monotonicity constraint (7) is met. This ensures incentive compatibility of the contract. We can also see that the above solution would hold even in the presence of the constraint $\pi_i^t \geq 0$ since (12) implies that $\dot{\pi}_i^t$ is non-negative and hence its integral function with respect to θ_i must also be non-negative.

With adverse selection, the optimal water quotas are smaller than the optimal quotas with full information, $w_i^{t^{**}} \leq w_i^{t^*}$ (see appendix for proof). This allows more junior right holders to use water. Equation (16) implies that we grant a zero profit for the farmer whose type is $\underline{\theta}$ ($\pi_i^t(\underline{\theta}) = 0$), therefore the proportion of farmers adopting the modern technology is $F\left(\theta^{**}\right)$. Since the profit expression in (7) is not analytically tractable, the technology adoption behavior of farmers is analyzed numerically.

Bilateral Water Trading under Asymmetric Information

We consider the potential for bilateral trading of water rights under adverse selection and explore the pattern of technology adoption induced by water trading. Consider two water users *i* and *j*, whose initial endowments of water are $w_i^{t^{**}}$ and $w_j^{t^{**}}$ as determined in the previous subsection. Their corresponding profits are $\pi_i^{t**}\left(w_i^{t**}, h_i^t(\theta_i)\right)$ and $\pi_j^{t**}\left(w_j^{t**}, h_i^t(\theta_j)\right)$. Farmers with types below θ^{**} adopt the modern irrigation technology while those with types above θ^{**} adopt the traditional technology. The reservation levels of profits for each water user are those achieved using the water quota and the choice of irrigation technology determined above. We assume that once the modern technology is adopted it cannot be abandoned.

If trade occurs between *i* and *j*, then $x_{ij} \equiv x_{ij}(\theta_i, \theta_j)$ denotes the quantity of water transferred from a farmer of type θ_i to a farmer of type θ_j for a monetary transfer of $m_{ji}(x_{ij})$, from *j* to *i*. When trade occurs the profit functions for *i* and *j* are respectively:

$$(18)\ \pi_i^t\left(x_{ij}, h_i^t\right) = P\left(-d + bh_i^t\left(w_i^{t**} - x_{ij}\right) - a\left(h_i^t\left(w_i^{t**} - x_{ij}\right)\right)^2\right) - k(w_i^{t**} - x_{ij}) - c^t - \Phi\left(w_i^{t**}\right) + m_{ji}(x_{ij})$$

$$(19)\ \pi_j^t\left(x_{ij}, h_j^t\right) = P\left(-d + bh_j^t\left(w_j^{t**} + x_{ij}\right) - a\left(h_j^t\left(w_j^{t**} + x_{ij}\right)\right)^2\right) - k(w_j^{t**} + x_{ij}) - c^t - \Phi\left(w_j^{t**}\right) - m_{ji}(x_{ij}).$$

Consider the existence of a benevolent broker or a facilitator, such as an irrigation district (Landry) or a water-bank (Howitt) whose objective is to maximize the sum of the seller and the buyer profits or the social gain generated by the trade. Under asymmetric information, the broker's problem is to use a revelation mechanism to induce agents *i* and *j* to reveal their types to the broker and to maximize the expected sum of their profits.

Let $\Pi_i\left(x_{ij}(\hat{\theta}_i, \theta_j), h_i^t(\theta_i)\right)$ be farmer *i*'s profit when he reports a type $\hat{\theta}_i$ to the broker while his true type is θ_i. Similarly for farmer *j* we have $\Pi_j\left(x_{ij}(\theta_i, \hat{\theta}_j), h_j^t(\theta_j)\right)$.

The broker maximizes the expected sum of profits:

$$(20)\qquad \max_{x_{ij}(.)} E_{\theta_i} E_{\theta_j}\left(\Pi_i(.) + \Pi_j(.)\right) \text{ such that;}$$

(21) $$E_{\theta_j}\Pi_i\left(x_{ij}(\theta_i,\theta_j),h_i^t(\theta_i)\right) \geq E_{\theta_j}\Pi_i\left(x_{ij}(\hat{\theta}_i,\theta_j),h_i^t(\theta_i)\right),$$

(22) $$E_{\theta_i}\Pi_j\left(x_{ij}(\theta_i,\theta_j),h_j^t(\theta_j)\right) \geq E_{\theta_i}\Pi_j\left(x_{ij}(\theta_i,\hat{\theta}_j),h_j^t(\theta_j)\right),$$

(23) $$\pi_i^t\left(x_{ij}(\theta_i,\theta_j),h_i^t(\theta_i)\right) \geq \pi_i^{t**}\left(w_i^{t**},h_i^t(\theta_i)\right),$$

(24) $$\pi_j^t\left(x_{ij}(\theta_i,\theta_j),h_j^t(\theta_j)\right) \geq \pi_j^{t**}\left(w_j^{t**},h_j^t(\theta_j)\right),$$

(25) $$0 \leq x_{ij}(\theta_i,\theta_j) \leq w_i^{t**}.$$

Constraints (21) and (22) are incentive compatibility constraints that ensure truth telling by farmers *i* and *j*, while constraint (25) limits the volume of trade to the endowments of the seller. Constraints (23) and (24) grant the trading parties a minimum level of profit equal to the profit they had before initiating any water trading. Here we require *ex-post* individual rationality, which implies that a farmer accepts a trade only if the realized profits are at least as large as those in the absence of trade.[3]

We use the incentive compatible constraints (26) and (27) to rewrite the objective function (25) as a sum of expected profits. For farmer *i*, truth-telling requires:

(26) $$\left.\frac{\partial E_{\hat{\theta}_j}\Pi_i\left(x_{ij}(\hat{\theta}_i,\theta_j),h_i^t(\theta_i)\right)}{\partial\hat{\theta}_i}\right|_{\hat{\theta}_i=\theta_i} = 0.$$

Using (26) we write the total derivative of $\Pi_i\left(x_{ij}(\theta_i,\theta_j),h_i^t(\theta_i)\right)$ with respect to θ_i as:

$$\text{(27)}\quad \begin{aligned}\frac{dE_{\theta_j}\Pi_i(.)}{d\theta_i} &= \frac{\partial E_{\hat{\theta}_j}\Pi_i(.)}{\partial h_i^t(.)}\frac{\partial h_i^t(.)}{\partial\theta_i} \\ &= \int_{\underline{\theta}}^{\overline{\theta}} P\Big(b\big(w_i^{t**}-x_{ij}(\theta_i,\theta_j)\big)\dot{h}_i^t(\theta_i) - 2a\big(w_i^{t**}-x_{ij}(\theta_i,\theta_j)\big)^2 h_i^t(\theta_i)\dot{h}_i^t(\theta_i)\Big) f(\theta_j)d\theta_j.\end{aligned}$$

A farmer whose type $\theta_i = \overline{\theta}$, will not be willing to sell water because no other agent with type $\theta_j < \overline{\theta}$ would be willing to pay a price that covers the marginal profit foregone by farmer *i*. Thus $\Pi_i\left(x_{ij}(\overline{\theta},\theta_j), h^t(\overline{\theta})\right) = \pi_i^{t**}\left(w_i^{t**}(\overline{\theta}), h^t(\overline{\theta})\right) = \overline{\pi_i}$, which is a constant. Indeed an agent whose type is $\overline{\theta}$ has the lowest quantity of water along with the highest productivity of water, as shown in the appendix. Integrating (27) between θ_i and $\overline{\theta}$, we obtain the incentive compatible profit for *i*:

$$\text{(28)}\ E_{\theta_j}\Pi_i(.) = \overline{\pi_i} - \int_{\theta_i}^{\overline{\theta}}\int_{\underline{\theta}}^{\overline{\theta}} P\Big(b\big(w_i^{t**}-x_{ij}(.)\big)\dot{h}_i^t(u) - 2a\big(w_i^{t**}-x_{ij}(.)\big)^2 h_i^t(u)\dot{h}_i^t(u)\Big) f(\theta_j)d\theta_j du\,.$$

In order to get the expected profits for farmer *i* in (20), we compute the expected profit of farmer *i* with respect to θ_i from (33) and use Fubini's theorem to get:

$$\text{(29)}\ E_{\theta_i\theta_j}\Pi_i(.) = \overline{\pi_i} - \int_{\underline{\theta}}^{\overline{\theta}}\int_{\underline{\theta}}^{\overline{\theta}}\int_{\theta_i}^{\overline{\theta}} P\big(w_i^{t**}-x_{ij}(.)\big)\dot{h}_i^t(u)\Big(b-2a\big(w_i^{t**}-x_{ij}(.)\big)h_i^t(u)\Big) f(\theta_j)f(\theta_i)\,du\,d\theta_j\,\,d\theta_i\,.$$

Observe that in addition to $\overline{\pi_i}$ which is fixed in (29), there is an additional quantity that represents the expected value of output forgone by *i* and gained by *j* when $x_{ij}\left(\theta_i,\theta_j\right)$ units of water are transferred from *i* to *j*.

The replication of the above steps for agent *j* is straightforward. If farmer *j* is a buyer then having a type equal to $\underline{\theta}$ would grant the agent a zero profit as required by the constraint (16) in the previous section. Applying the same procedure as in equations (26) through (29), we obtain the incentive-compatible expected profits for farmer *j*:

$$(30)\; E_{\theta_j\theta_i}\Pi_j\left(.\right)=\int_{\underline{\theta}}^{\bar{\theta}}\int_{\underline{\theta}}^{\bar{\theta}}\int_{\underline{\theta}}^{\theta_j}P\left(w_j^{t**}+x_{ij}(.)\right)\dot{h}_j^t(u)\left(b-2a\left(w_j^{t**}+x_{ij}(.)\right)h_j^t(u)\right)f(\theta_i)\,f(\theta_j)\;du\;d\theta_i\;d\theta_j\,.$$

Expressions (29) and (30) transform the broker's problem to maximizing the sum of incentive-compatible expected profits with respect to the optimal amount of water transfer $x_{ij}\left(\theta_i,\theta_j\right)$ accompanied by a monetary transfer of $m_{ji}(x_{ij})$ which satisfies constraints (23)-(25). If we assume the absence of transaction costs related to water trading, then $m_{ji}(x_{ij})$ cancels when we sum (29) and (30). Applying Leibniz's rule to maximize the sum of (29) and (30) with respect to $x_{ij}\left(\theta_i,\theta_j\right)$ and simplifying we obtain the following first order condition:

$$(31)\int_{\underline{\theta}}^{\theta_j}\dot{h}_j^t(u)\left(b-4a\left(w_j^{t**}+x_{ij}(\theta_i,u)\right)h_j^t(u)\right)du=\int_{\theta_i}^{\bar{\theta}}\dot{h}_i^t(u)\left(-b+4a\left(w_i^{t**}-x_{ij}(u,\theta_j)\right)h_i^t(u)\right)du\,.$$

If we take the derivative with respect to θ_i and then with respect to θ_j on both sides, we get the first order condition expressed in the following homogenous parabolic linear partial-differential equation of order one and degree one in $x_{ij}\left(\theta_i,\theta_j\right)$:

$$(32)\qquad h_j^t(\theta_j)\dot{h}_j^t(\theta_j)\frac{\partial x_{ij}(.)}{\partial\theta_i}+h_i^t(\theta_i)\dot{h}_i^t(\theta_i)\frac{\partial x_{ij}(.)}{\partial\theta_j}=0\,.$$

So far, when we introduced adverse selection, we assumed that farmer *i* is the seller and that farmer *j* is the buyer. In fact, regardless of the way we setup the trading problem the trading rule derived in (32) remains unchanged and designating one agent as buyer and the other as seller is irrelevant.[4]

Proposition 2: Consider a social gain-maximizing independent broker and two agents *i* and *j* with initial endowments w_i and w_j in a given divisible good and private valuations for the good. As long as the expected social gain is positive, the broker is able to determine an incentive compatible trading rule that determines the optimal quantity to trade and its direction irrespective of the agents' true valuations for the good.

In this setting, a broker acting as the Walrasian auctioneer who matches the buyers and the sellers without seeking gains from the transaction, can bring about mutually beneficial agreements between buyers and sellers. In our setting, it is important that the broker is independent and different from the water authority that assigns the initial endowments in water. This ensures that the quantities $w_i^{t^{**}}(\theta_i)$ and $\Phi\left(w_i^{t^{**}}(\theta_i)\right)$, determined in the previous subsection, are considered constants by the broker, thus excluding any renegotiation of the contract between the regulator and the farmers.

If we omit the constant terms, the anti-derivative of $h^t(\theta_i)\dot{h}^t(\theta_i)$ is $\frac{1}{2}\left(\frac{\theta_i-\underline{\theta}}{\overline{\theta}-\underline{\theta}}\right)^{2\alpha_i}$ and for $h^t(\theta_j)\dot{h}^t(\theta_j)$ it is $\frac{1}{2}\left(\frac{\theta_j-\underline{\theta}}{\overline{\theta}-\underline{\theta}}\right)^{2\alpha_j}$. With C_0 and C_1 being constants, the general solution for (32) is then obtained as follows:

(33) $x_{ij}\left(\theta_i,\theta_j\right)=C_0\cdot\left(\frac{2}{2\alpha_j+1}\left(\overline{\theta}-\underline{\theta}\right)^{2\alpha_i}\left(\theta_j-\underline{\theta}\right)^{2\alpha_j+1}-\frac{2}{2\alpha_i+1}\left(\overline{\theta}-\underline{\theta}\right)^{2\alpha_j}\left(\theta_i-\underline{\theta}\right)^{2\alpha_i+1}\right)+C_1.$

Expression (33) is a general solution to (32); if farmers are identical no trade occurs; therefore $C_1=0$. The constant C_0 is a scaling factor that is determined such that:

(34)
$$C_0\left(i,j\right)=\frac{\max\left\{w_i^{t**};\forall i\right\}}{\max\left\{K\left(\theta_i,\theta_j\right);\forall\left(i,j\right)\right\}},$$

where $K\left(\theta_i,\theta_j\right)=\frac{2}{2\alpha_j+1}\left(\overline{\theta}-\underline{\theta}\right)^{2\alpha_i}\left(\theta_j-\underline{\theta}\right)^{2\alpha_j+1}-\frac{2}{2\alpha_i+1}\left(\overline{\theta}-\underline{\theta}\right)^{2\alpha_j}\left(\theta_i-\underline{\theta}\right)^{2\alpha_i+1}$.

Now that the optimal water-trading rule is determined, we direct our attention to constraints (23)-(25) of the broker's problem. Let us denote the optimal level of water trading by x_{ij} found in (33). For this level to be feasible, it has to be accompanied by a monetary transfer given by the expressions below. The final level of transfer will be determined through negotiation between the trading parties:

(35) $m_{ji}(x_{ij})\geq\pi_i^{t**}-P\left(-d+bh^t(\theta_i)\left(w_i^{t**}-x_{ij}\right)-a\left(h^t(\theta_i)\left(w_i^{t**}-x_{ij}\right)\right)^2\right)+k\left(w_i^{t**}-x_{ij}\right)+c^t+\Phi_i^{**}$

(36) $m_{ji}(x_{ij})\leq P\left(-d+bh^t(\theta_j)\left(w_j^{t**}+x_{ij}\right)-a\left(h^t(\theta_j)\left(w_j^{t**}+x_{ij}\right)\right)^2\right)-k\left(w_j^{t**}+x_{ij}\right)-c^t-\Phi_j^{**}-\pi_j^{t**}.$

Since the water quotas determined by the regulator in the previous subsection are decreasing across farmers' types, it is expected that the higher the farmers' type the higher is his marginal valuation for water. This indicates that for trading to generate the highest social gain the lower type must be selling to the higher type farmers. This implies that at the conclusion of the trade it is possible that some of the lower type farmers who sell part of their water quota will use their water sales revenues to adopt the modern technology. The adoption of the modern technology occurs when post trade incremental net benefits of the modern irrigation technology exceed its cost as stated by the following condition:

$$(37) \qquad P\left(w_i^{L**} - x_{ij}\right)\left(h_i^H(\theta_i) - h_i^L(\theta_i)\right)\left[b - a\left(w_i^{L**} - x_{ij}\right)\left(h_i^H(\theta_i) + h_i^L(\theta_i)\right)\right] \geq c^H .$$

In this section, we showed that the existence of adverse selection makes water regulation inefficient even if a nonlinear pricing scheme is devised. We then examined the use of water trading as a policy to increase the efficiency of water allocation and devised a trading rule that is incentive compatible. If condition (37) is fulfilled, additional technology adoption by the sellers is to be expected. The existence of water trading allows for a better allocation of resources across farmers and gives incentives to adopt better irrigation technologies, while increasing the social welfare in comparison to the non-trading solution. However, intuitively the additional adoption of irrigation technologies cannot approach the first best level. This is because the presence of informational asymmetries prevents some transactions that would be possible under full information from occurring. In the following section, we provide additional insights by numerically simulating the model developed above.

Numerical Illustration and Additional Insights

For illustration, we use a quadratic production function with $d = 6$, $b = 10.68$, and

$a = 1.7$, based on data from southern California and Arizona for fruits and vegetables production (Caswell and Zilberman). Output price is assumed to be $100 per unit of output. The additional setup costs required to adopt the modern technology range between $50 and $100 per acre; we use the value of $c^H = \$75$ per acre to illustrate our results. Irrigation effectiveness for the traditional technology is different from that with the modern technology and depends on the coefficient α_i. Caswell and Zilberman report that in western United States when $\theta_i = 0.6$ the effectiveness of the modern technology (drip), $h^H(0.6) = 0.95$ implying that $\alpha_i = 0.1, \forall i$.[5] We assume that the private cost of the energy to pump water from its source to the field is *k*=15 per acre-foot of water, as in Caswell and Zilberman where water is pumped from a well.[6] We assume also that farmers are charged $g = \$80$ per acre-foot of water. We take the average social cost of public funds $\lambda = 0.3$ reported by Boyer and Laffont (p. 140) for developed economies. The farmers' type, θ_i, is defined over the support $[0,10]$, and has a density $f(\theta_i) = \dfrac{z(\theta_i)}{Z(\overline{\theta}) - Z(\underline{\theta})}$, where *z* is a Gaussian distribution with mean $\dfrac{\overline{\theta} + \underline{\theta}}{2}$ and variance 1, and *Z* its cumulative distribution.

The incentive compatible profits under these assumptions are plotted in figure 1.a, and show that the introduction of adverse selection significantly reduces the adoption of modern technology relative to that under full information. Under full information the critical value of farmer's type below which the modern technology is adopted and above which the traditional technology is maintained is $\theta^* = 7.66$. Under adverse selection, the threshold level for technology switching is located at a much lower level ($\theta^{**} = 5.22$) than under full information. Figure 1.b depicts the optimal water quantity for every farmer's type under full information and under adverse selection. Both curves are piecewise monotonically decreasing with a discontinuity at the critical θ levels where there is a switch in the technology adopted.[7] The dashed line shows that under adverse selection, water quotas assigned to the low type farmers using the modern technology and the very high type farmers using the traditional technology are smaller than under full information while medium type farmers receive higher water quotas than under full information. These water quotas and equation (6) are used to compute the water fees depicted in figure 1.c.[8] These show that under adverse selection most farmers (except some of the medium type) pay a lower water fee compared to the full information case. Given the distortions introduced by adverse selection one might ask why the regulator does not retire the contract that allows for low technology adoption and offers only the one that requires the use of the modern technology. Doing so would significantly lower the profits of the most productive farmers; in practice, those farmers might choose not to farm any more and only low productivity farmers will remain in the sector, which obviously is not desirable from the point of view of the regulator.

Figure 1.d depicts the social gain functions and it shows, as expected, that under full information the socially desirable threshold level for switching technology is at a higher level than the level determined by the farmers in figure 1.a. However, because of informational rents and because farmers do not take into account the cost of public funds λ, the socially desirable switching point under adverse selection is at a lower level than

the level determined by the farmers ($\theta = 5.13$ instead of 5.22). In principal-agent models, it is expected that the social gain obtained under adverse selection will be lower than the social gain under full information if all other elements of the model, such as the water fee schedule remain the same. In our model, the pricing schedule is different across the two scenarios for reasons explained above. With the traditional technology, the water fee under adverse selection is lower for almost all farmers' types in general and for the highest types in particular who maintain an almost unchanged level of water quotas under both the full and asymmetric information cases. Therefore the high types are able to generate more net value which explains their higher level of social gain under asymmetric information when $t = L$.

The results above show that the introduction of adverse selection and the use of nonlinear and discriminative water pricing although leading to a lower level of water quotas, induces a lower level of technology adoption. The reduction in technology adoption is due to low water fee when $t = L$ this induces some farmers to keep the traditional technology rather then switch to the modern technology. We now examine if a move toward water trading might lessen the distortions produced by adverse selection.

We are interested in examining the potential for trading and for additional technology adoption in the range of $\theta > \theta^{**}$. These are the types that found it more profitable to adopt the traditional technology under adverse selection. We therefore focus on the range of $\theta > \theta^{**} = 5.22$ shown in figure 1.a. In figure 2.a we provide a contour plot of possible trade levels from a farmer of type θ_i to a farmer of type θ_j as determined by the trading rule in (33).[9] It shows that the highest possible, not necessarily feasible, trading occurs when $\left(\theta_i, \theta_j\right) \in \left[\theta^{**}, \overline{\theta}\right]^2$. The positive and negative values of the contours indicate that in the region above the 45-degree line, farmer *j* is a buyer since his marginal valuation of water is higher than that of farmer *i*. Below the 45-degree line *j* will be the seller and *i* is the buyer, for illustration we are focusing on trades with *i* as seller and *j* as buyer and have labeled the axis accordingly. By symmetry, one can show corresponding areas below the 45-degree line where *j* is the seller and *i* is the buyer. These results are consistent with the intuition that farmers with high marginal valuations for water will be water buyers and farmers with low marginal valuation for water will be water sellers.

For a trade level to be feasible it has to be met by a monetary transfer that fulfills (35) and (36). In figure 2.a, we highlight the feasible levels of trade from *i* to *j* leading to the adoption of the modern technology ($\left(\theta_i, \theta_j\right) \in \left[\theta^{**}, \overline{\theta}\right]^2$) as determined by condition (37). Trade by lower levels of θ_i, that is $\left(\theta_i, \theta_j\right) \in \left[\theta^{**}, \overline{\theta}\right] \times \left[\underline{\theta}, \theta^{**}\right]$ do not lead to the adoption of the modern technology. They only lead to minor adjustments of water use across farmers. Trade leads to additional modern irrigation technology adoption when the net gains of technology adoption are higher than the cost of adoption as depicted in condition (37).

The above analysis gives an assessment of the possible trades that farmers of different types may engage in and their implications for technology adoption. The final level of monetary transfer is determined through negotiation between the seller and the buyer, and cannot be determined within the framework presented here. Nevertheless, for various potential water trade levels that induce modern irrigation technology adoption, represented in the contour plot in figure 2.a, we show the monetary transfers above the reservation level in (35) that would support them in figure 2.b. Figure 2.b is a zoom-in on the combinations of θ_i and θ_j that would lead to modern irrigation technology adoption. We find that some water volumes can be traded for up to $50 above the reservation level in (35). For a given buyer's type θ_j, as the seller's type θ_i moves away from $\theta^{**} = 5.22$ the seller's potential surplus decreases, i.e. the interval for $m_{ji}\left(x_{ij}\right)$ defined by (35) and (36) shrinks and monetary transfer he is willing to make decreases.

Conclusion

We showed that adverse selection induces less technology adoption than full information but that even under adverse selection, bilateral water trading among farmers can reduce the distortion created in the allocation of water quotas relative to the situation with full information. Water trading is shown to occur for two reasons. First, they occur for minor adjustments amongst low type farmers who have already adopted the modern irrigation technology and second, they occur between farmers who did not adopt the modern irrigation technology. In the latter case, water is transferred from low type farmers to higher type farmers. In this case, it is possible that the revenues from water transfer enable the adoption of modern technology but not to reach a first best level. The results of the numerical analysis showed that the existence of a second phase of trading after the regulator initially allocates the water quotas generates important social gains and induces additional technology adoption that the initial allocation of water resources could not achieve alone.

In developing the model in this article, we considered only one-shot games and excluded contract renegotiation. In the context of water rights, this assumption is not restrictive since water rights usually span a long period; therefore, each time the contract is designed past information is of little relevance. We have also overlooked the existence of transaction costs related to trade; some studies show substantial gains from water trading compared to its transaction costs (Easter). In the model above, we assumed that the private cost *k* is not type-dependent. However, we suspect that an extension of the model where *k* is decreasing with respect to the farmer's type will not introduce a qualitative change to the results. Since water use is decreasing with respect to the farmer's type, the total private cost $kw_i^t(\theta_i)$ is also decreasing with respect to farmer's type. Parameterizing *k* will not produce countervailing incentives to alter the above revelation mechanism. A better alternative to pricing could be an auction of water rights instead of the determination of water quotas by the regulator and a second market to correct for any inefficient allocation of water rights. Water auctions have been used in Victoria, Australia (Simon and Anderson). However, the results of the auction depend on the auction rules selected and on the capacity of the regulator to prevent cheating and rigging. Additionally, the implementation of water auctions seems to be more suitable for new water resources where no previous rights could be claimed and not for the case with prior appropriation rights on water examined here.

Appendix

Optimal Water Quota: Full Information vs. Adverse Selection

We compare the optimal water quota obtained under full information with the one obtained with adverse selection, we check if $w_i^{t^{**}}$ is less than $w_i^{t^*}$,

(A1) $$\frac{Pb\left((1-\lambda)h^t + \lambda \dot{h}^t R(\theta_i)\right) - \left(g + k(1-\lambda)\right)}{2aPh^t\left((1-\lambda)h^t + 2\lambda \dot{h}^t R(\theta_i)\right)} \leq \frac{b}{2ah^t(\theta_i)} - \frac{k + g(1+\lambda)}{2aP\left(h^t(\theta_i)\right)^2}.$$

A simplification and rearrangement of (A1) gives:

(A2) $$0 \leq gh\lambda^2 + \lambda \dot{h}^t R(\theta_i)\left(Pbh^t - 2k - 2g(1+\lambda)\right).$$

Recall that $w_i^{t^*} = \frac{b}{2ah^t(\theta_i)} - \frac{k + g(1+\lambda)}{2aP\left(h^t(\theta_i)\right)^2}$ and considering our assumptions we get:

(A3) $$\frac{b}{4ah^t(\theta_i)} - \frac{k + g(1+\lambda)}{2aP\left(h^t(\theta_i)\right)^2} > 0.$$

Expression (A3) implies that $Pbh^t - 2k - 2g(1+\lambda) > 0$, therefore expression (A2) is indeed positive; therefore, the water quota under adverse selection is less than the water quota under full information, $w_i^{t^{**}} < w_i^{t^*}$.

[1] http://www.wrd.state.or.us , http://www.idwr.state.id.us/water , http://water.state.co.us/ , http://nrwrt1.nr.state.ut.us

[2] To keep matters simple, we assume that there is no market power and no third party effects related to the transfer or trade of water rights. Saleth, Braden, and Eheart, address those issues under full information.

[3] This is a much stronger requirement than the *interim* individual rationality requirement where constraints (23) and (24) would be replaced by their expected values (Gresik).

[4] If we assume that $x_{ij}(.)$ is negative and replace $x_{ij}(.)$ by $-x_{ji}(.)$, (32) remains unchanged.

[5] We assume that α_i is the same for all farmers irrespective of θ_i.

[6] This cost is not relevant here but for generality, we include it in the analysis.

[7] Under adverse selection, the monotonicity condition is not always fulfilled as is the case here for low values of θ. We force monotonicity by bunching together lower values of $\theta \leq 4.06$ (see Laffont and Tirole, p. 121-123).

[8] To compute the integral function in (6), we use the summed quadrature formula $\int_a^b f(t)dt = \lim_{dt \to 0} \sum_{n=0}^{\frac{b-a}{dt}} \left(f(a+ndt).dt \right)$ with step size $dt = 1/1000$.

[9] Water trading from a farmer of type θ_j to a farmer of type θ_i are symmetric to the trade from a farmer of type θ_i to a farmer of type θ_j, they are represented with negative value in the contour plot of figure 2.a.

References

Boyer, M., and J-.J. Laffont. "Toward a Political Theory of the Emergence of Environmental Incentive Regulation." *Rand Journal of Economics* 30 (1999): 137-57.

Burness, H.S., and J.P. Quirk. "Water Law, Water Transfers, and Economic Efficiency: The Colorado River." *Journal of Law and Economics* 23 (1980): 111-34.

Carey, J.M., and D. Zilberman. "A Model of Investment under Uncertainty: Modern Irrigation Technology and Emerging Markets in Water." *American Journal of Agricultural Economics* 84 (2002): 171-83.

Caswell, M.F., and D. Zilberman. "The Effects of Well Depth and Land Quality on the Choice of Irrigation Technology." *American Journal of Agricultural Economics* 68 (1986): 798-811.

Caswell, M.F., D. Zilberman, and G. Casterline. "The Diffusion of Resource-Quality-Augmenting Technologies: Output Supply and Input Demand Effects." *Natural Resource Modeling* 7 (1993): 305-29.

Caswell, M.F., E. Lichtenberg, and D. Zilberman. "The Effects of Pricing Policies on Water Conservation and Drainage." *American Journal of Agricultural Economics* 72 (1990): 883-90.

Dinar, A., and J. Letey. "Agricultural Water Marketing, Allocative Efficiency, and Drainage Reduction." *Journal of Environmental Economics and Management* 20 (1991): 210-23.

Easter, K.W. "Water Markets and Other Mechanisms to Decentralize and Improve Water

Management." Working Paper, Fondazione ENI Enrico Mattei, Milan, 1994.

Freyfogle, E.T. "Water Rights and the Common Wealth." *Environmental Law* 26 (1996): 27-51.

Gresik, T.A. "Ex Ante Efficient, Ex Post Individually Rational Trade." *Journal of Economic Theory* 53 (1991): 131-45.

Howitt, R.E. "Empirical Analysis of Water Market Institutions: The 1991 California Water Market." Working Paper, Fondazione ENI Enrico Mattei, Milan, 1994.

Khanna, M., M. Isik, and D. Zilberman. "Cost-Effectiveness of Alternative Green Payment Policies for Conservation Technologies Adoption with Heterogeneous Land Quality." *Agricultural Economics* 27 (2002): 157-74.

Laffont, J.-J., and J. Tirole. *A Theory of Incentives in Procurement and Regulation*. Cambridge MA: MIT Press, 1993.

Landry, J.C. *Saving our Streams through Water Markets: A Practical Guide*. Bozemon, MT: Political Economy Research Center, 1998.

Livingston, M.L. "Designing Water Institutions: Market Failures and Institutional Response." Policy Research Working Paper, The World Bank, Washington DC, 1993.

———. "Institutional Requisites for Efficient Water Markets." *Markets for Water: Potential and Performance*. K.W. Easter, M.W. Rosegrant and A. Dinar, eds., pp. 19-33. Massachusetts: Kluwer Academic Publishers, 1998.

Saleth, R.M., J.B. Braden, and J.W. Eheart. "Bargaining Rules for a Thin Spot Water Market." *Land Economics* 67 (1991): 326-39.

Shah, F., D. Zilberman, and U. Chakravorty. "Water Rights Doctrine and Technology Adoption." *The Economics of Rural Organization: Theory, Practice, and Policy*. K. Hoff, A. Braverman and J. Stiglitz, eds., pp. 479-499. New York NY: Oxford University Press, 1993.

Simon, B., and D. Anderson. "Water Auctions as an Allocation Mechanism in Victoria, Australia." *Water Resources Bulletin* 26 (1990): 387-95.

Smith, R.B.W., and Y. Tsur. "Asymmetric Information and the Pricing of Natural Resources: The Case of Unmetered Water." *Land Economics* 73 (1997): 392-403.

U.S. Department of the Interior, Bureau of Reclamation. *Incentive Pricing Handbook for Agricultural Water Districts,* Washington DC, April 1997.

Zilberman, D., N. MacDougall, and F. Shah. "Changes in Water Allocation Mechanisms for California Agriculture." *Contemporary Economic Policy* 12 (1994): 122-133.

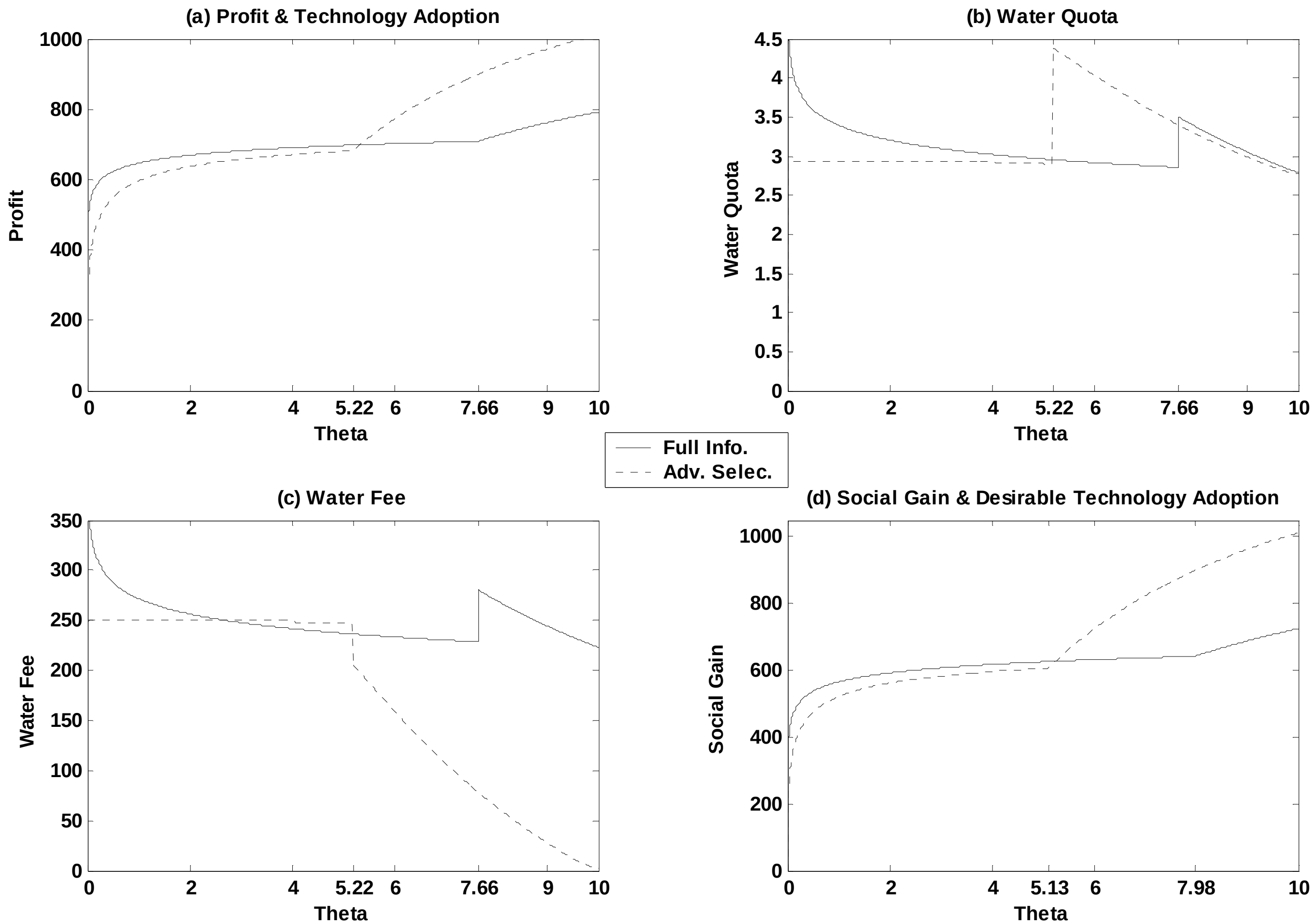

Figure 1: Water quotas and fees, profits, and social gains under full information and adverse selection

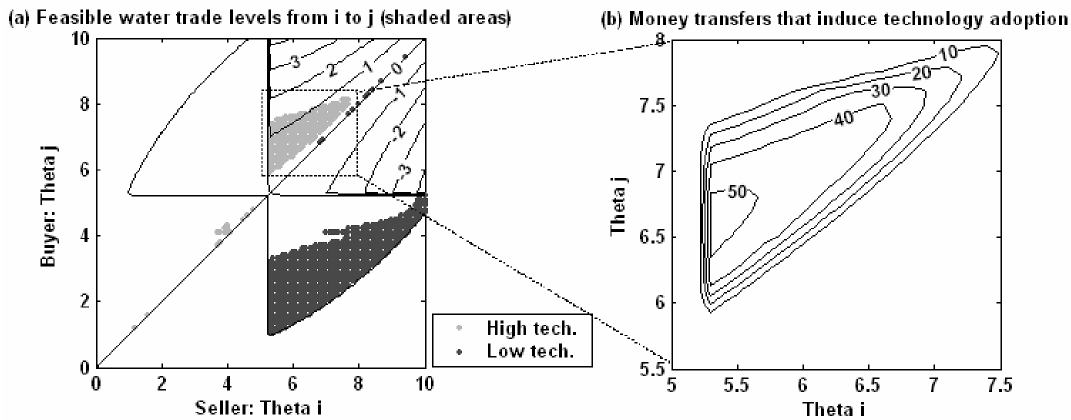

Figure 2: Water trading and technology adoption feasibility