

Efficacy of Water Trading under Asymmetric Information and Implications for Technology Adoption

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EFFICACY OF WATER TRADING UNDER ASYMMETRIC INFORMATION AND IMPLICATIONS FOR TECHNOLOGY ADOPTION

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ABSTRACT: The purpose of this paper is to develop a water allocation and technology adoption model under the prior appropriation doctrine that recognizes informational asymmetry among water users and between water users and water authorities. We consider informational asymmetry about the agent's type, defined by a mix of land quality and knowledge. Adverse selection is found to significantly reduce the adoption of modern irrigation technology and to lead to less retirement of poor quality lands than under full information. Further investigation shows that even with asymmetric information, incentives for water trades can exist and lead to additional technology adoption with gains to all parties. Our results suggest that under asymmetric information, even a thin secondary market can improve the allocation of water resources.

Keywords: Adverse selection, Asymmetric information, Prior appropriation, Technology adoption, Water rights, Water trading.

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INTRODUCTION

Although markets have the potential for allocating scarce resources for which property rights have been well defined in an efficient manner, agricultural water markets are not unanimously accepted as being an efficient mechanism for allocating scarce water resources among agricultural producers. Authors like Freyfogle consider that "many of the inefficiencies have to do with imperfect information, transaction costs, and inadequate numbers of willing buyers and sellers" while Livingston (1993) argues that markets for water fail to achieve efficiency because water use "suffers from information deficiencies" among other reasons. These information deficiencies may arise because farmers are heterogeneous in their soil conditions and thus in the value of water to them (Freyfogle) and because stochastic factors influence and the relationship between applied water and agricultural output (Saliba and Bush). Information asymmetry might exist regarding land quality and input requirements under different weather conditions between water users themselves and between the regulator and water users.

Asymmetric information may also impede the determination of water quotas under the prior appropriation doctrine which in a number of regions assigns not only a seniority rule for water usage but also limits water use through quotas determined by water authorities. A close reading of the legislation of some countries like Japan (Nakashima) or some states in the US (e.g. Oregon, Idaho, Colorado, and Utah) reveals that the date and time stamp on the application establish the priority of the right. The water quota and fees for the water are determined by the water agency according to the intended use and the availability of the resources. The U.S. Bureau

of Reclamation recommends setting water rates that would lead to efficient use of water but recognizes the difficulties that might arise from "gathering the technical details to support the design and administration of workable rate schedules." Water quotas and fees determined either by the water agency or by water markets can affect both the quantity of water used and choice of irrigation technologies which determine the effectiveness with which that water is used for irrigation.

In this paper, we develop a framework to examine the determination of water quotas and water fees to allocate scarce water among farmers, while recognizing the prevailing prior appropriations doctrine and the informational asymmetry about the farmer's type, defined by a mix of land quality and knowledge. We develop a mechanism to price irrigation water and assign water quotas, and examine its implications for adoption of modern irrigation technologies and water use as compared to those under full information. We then establish conditions under which a water market could induce trading and additional technology adoption and thereby increase social welfare. Our model is appropriate for surface water used by farmers in agriculture. We have limited the study to the agricultural uses of water since more than 70% of surface water resources are being used for agricultural purposes. In our model, water allocation is based on the prior appropriation doctrine which is widely prevailing, in the United States, where water experience is the most documented. We focus on water trading in a thin spot-market; this naturally implies that water sellers enjoy a limited market power, since the upper bound for prices depends on water marginal productivity for the buyers. Because of the bulkiness of water, for any trade to occur it has to be geographically confined and most likely among few water users, which justifies the thinness of the market. In addition, we assume away

any third-party effects¹ related to the transfer or trade of water rights. This limitation is not without consequences but to keep matters simple we do not address that issue here (for a treatment involving market power and third-party effects under full information see Saleth et al.).

Our study differs from existing literature on irrigation technology adoption and water markets in several ways. There are several studies that have focused only on analyzing technology adoption decisions under perfect information (Caswell and Zilberman) and uncertainty about water availability (Carey and Zilberman) or examined the design of incentive compatible mechanisms for water pricing under the riparian doctrine (Smith and Tsur). Caswell and Zilberman assume that farmers have access to water without regulation on quantities in a full information context while Smith and Tsur focus on water pricing with riparian rights and with asymmetric information. They do not consider the possibility of water trading concerns or technology adoption. Carey and Zilberman, show that under uncertainty about water availability, water markets increases (decreases) the incentive to adopt modern irrigation technology for farmers with abundant (scarce) water quotas. Shah et al., consider water trading under full information and show that in the absence of water trading, senior water right holders have no incentives to adopt modern irrigation technology and they irrigate all their land, which leaves the junior right holder with little or no water. Existing studies show that water markets for surface water for agricultural uses are efficient under perfect information and create incentives for adoption of modern irrigation technologies (Dinar and Letey; Shah et al.). However they ignore an important aspect of the problem, namely the inefficiencies in water use and pricing introduced by asymmetric information and whether water markets may, even then, improve efficiency relative to the status quo.

¹ The change in the pattern of water use might generate additional pollution related to return flows and lower water levels that might affect economic activities located downstream.

Water Trading and Technology Adoption under Asymmetric Information

In addition to a two-sided information asymmetry, what distinguishes our trading situation from most bilateral bargaining literature (Myerson and Satterthwaite; McKelvey and Page) is that both buyer and seller have a positive initial endowment in the traded good, here water rights. This distinction implies that trade is not confined to a single direction; rather it can exist in either direction. Myerson and Satterthwaite showed that a direct revelation mechanism leading to trade might not always exist and that such mechanism is not always *ex-post* efficient. Their work is based on a single indivisible item where the buyer and the seller utilities are linear. McKelvey and Page generalized the work of Myerson and Satterthwaite to the case of a divisible item and nonlinear utilities to show in addition that under adverse selection there is a bias toward the status quo. For the above authors the existence of trade was compromised by the indivisibility of the good and by the unilateral endowment of resources.

The main results of the paper are that adverse selection leads to less adoption of modern irrigation technology and to less retirement of poor quality lands. However when an incentive mechanism is designed through a discriminatory pricing mechanism, water quotas for senior right holders can be reduced thus allowing for more junior right holders to use water. This comes at the expense of lower water fees collected from the high quality farmers who use the traditional irrigation technology. We find that when adverse selection prevails between the water agency and the farmers, the use of incentive mechanism alone cannot achieve the best allocation of water by the regulator and that a secondary water trading phase or "second market" should be considered to improve the allocation of water. We show that even under asymmetric information, surface water markets can increase social efficiency of water allocation and lead to more modern irrigation technology adoption than the non-trading situation. Allowing water trading has the potential to mitigate some of the inefficiencies due to adverse selection without

inducing further budgetary strain on the regulator, while inducing more modern technology adoption.

This paper is organized as follows; in the next section, we describe and discuss our model and its assumptions. In section three, we start with a benchmark version of the model where information is symmetric, as in Caswell and Zilberman and there is no water trading but water use is regulated. In section four, we introduce adverse selection and examine its implications in the absence of water trading. We then examine how water trading offers a correction to some of the inefficiencies generated by adverse selection. In the fifth section, we present a numerical illustration to gain more insights that could not be obtained analytically. In the conclusion, a summary of the results and discussion of the shortcomings and extensions conclude the paper.

THEORETICAL MODEL

We consider N farmers, indexed by $i=1, \dots, N$ according to the seniority of their water rights producing the same crop and facing an output price P . Farmers are heterogeneous in their type (e.g. land quality and skills) denoted by θ_i which is assumed to be independently distributed with density $f(\theta_i)$ and a cumulative distribution $F(\theta_i)$ over the support $[\underline{\theta}, \bar{\theta}]$. Farmers are assumed to have a choice of two irrigation technologies, $t = L, H$ where L is the traditional technology (such as furrow irrigation) and H is the modern technology such as sprinkler or drip.

The irrigation effectiveness of technology t for farmer i is represented by $h_i^t(\theta_i) = \left(\frac{\theta_i - \underline{\theta}}{\bar{\theta} - \underline{\theta}} \right)^{\alpha_i}$,

where $\alpha_i = 1$ if the traditional technology is adopted ($t = L$) and $\alpha_i \in]0, 1[$ if the modern

technology is being adopted ($t = H$)². The function $h_i^t(\cdot)$ can be thought of as the percentage of water absorbed or used effectively by the plant, hence it is bounded by 1 at $\theta_i = \bar{\theta}$. Regardless of the technology adopted, the percentage of water absorbed by the plant is zero at $\theta_i = \underline{\theta}$ which is the case if land is sandy, steep, or rocky. For realistic values of α_i , $h_i^H(\theta_i) > h_i^L(\theta_i)$ and the difference decreases as θ_i increases; thus the modern irrigation technology benefits farmers with low types more than those who have high types. The fixed cost per acre of the traditional technology is $c^L = 0$, while of the modern technology is $c^H > 0$. Assuming constant returns to scale and a quadratic functional form, the production function for farmer i is, $y_i(w_i^t, h_i^t(\theta_i)) = \max\{-d + b(w_i^t h_i^t(\theta_i)) - a(w_i^t h_i^t(\theta_i))^2, 0\}$, where y_i is yield per acre, $a > 0, b > 0$, and $d \geq 0$ are constants and w_i^t is the quantity of water used per acre by farmer i using technology t .

Assumption 1: The quadratic production function suggests the existence of a water quantity yielding a maximum output at $b - 2ah_i^t(\theta_i)w_i^t = 0$ for all $\theta_i \in]\underline{\theta}, \bar{\theta}]$, therefore we

assume that $w_i^t \leq \frac{b}{2ah_i^t(\theta_i)}$.

For every unit of water, there is a private cost k of diverting water from its source to the field. Additionally, the per-unit cost of water is g . The profit function for farmer i under technology t is thus defined by:

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

² Caswell and Zilberman define land quality to be the same as irrigation effectiveness under the traditional technology and taking values from $[0, 1]$. For generality, in our model we make a distinction between the parameter of land quality or agents' types, $\theta_i \in [\underline{\theta}, \bar{\theta}]$, and the effectiveness of irrigation technology, $h_i^t(\theta_i)$.

The total quantity of water available to farmers in the region is \bar{w} ; farmers divert water according to the prior appropriation doctrine, the priority is set when they apply for water rights.

Assumption 2: We consider that water is scarce; in the sense that there is, no configuration of θ_i 's under which all farmers can maximize their profits simultaneously.

Without the above assumption, any study of water allocation is pointless; an implication of this assumption is that for different allocation schemes there are some farmers who may be left without water. Recall that under the prior appropriation doctrine when there is water shortage, only the senior rights holders receive their quotas of water while the rest of the rights remain partially or completely unfulfilled.

If we denote by $e_i^t = h_i^t(\theta_i)w_i^t$, the quantity of effective water used when technology t is being implemented, Caswell and Zilberman define the elasticity of marginal productivity of effective water by $emp_i^t = -e_i^t \frac{\partial^2 y / \partial e_i^{t^2}}{\partial y / \partial e_i^t}$, and show that the optimal quantity of applied water w_i^t is decreasing with respect to the farmer's type³ if $emp_i^t > 1$.

Assumption 3: For $e_i^t = h_i^t(\theta_i)w_i^t$, we assume that $emp_i^t = -e_i^t \frac{\partial^2 y / \partial e_i^{t^2}}{\partial y / \partial e_i^t}$ is greater than one, implying that $w_i^t > \frac{b}{4ah_i^t(\theta_i)}$ for all i and t and water use is decreasing with respect to the farmer's type, $\frac{dw_i^t(\theta_i)}{d\theta_i} < 0$.

³ Caswell and Zilberman argue that cases where the quantity of applied water is an increasing function of types, are not realistic and not supported neither by production theory nor by empirical evidence, example of such functions includes the Cobb-Douglas production function.

Considered together, assumptions 1 and 3 imply that in order to be X-efficient with elasticity of marginal productivity greater than 1, water allocation has to be bounded by $\frac{b}{4ah'_i(\theta_i)}$ from below and by $\frac{b}{2ah'_i(\theta_i)}$ from above. For $\theta_i \in [\underline{\theta}, \theta^s]$, where θ^s solves $\pi_i^L = \pi_i^H$ such that $\pi_i^H > 0$, farmers adopt the modern technology ($t=H$) since $\pi_i^H \geq \pi_i^L$ and $\pi_i^H > 0$, for $\theta_i \in [\theta^s, \bar{\theta}]$ the traditional technology is selected ($t=L$), therefore the proportion of farmers adopting the modern irrigation technology is $F(\theta^s) - F(\theta^z)$, where θ^z is such that $\pi_i^H = 0$.

WATER ALLOCATION UNDER FULL INFORMATION: PRIOR APPROPRIATION DOCTRINE

In this section, we consider the problem of the regulator who has to decide on water quotas for every water user while recognizing the seniority of the farmer and the constraint on total water availability. The regulator determines each farmer's quota to maximize the social benefit generated by that allocation.

Livingston (1998) reports the existence of water commissioners who act as "River Cops", who monitor the use of water and ensure that it respects the established priorities and allocation levels. Such activity is costly to society and the per-monetary-unit cost is represented by $1 > \lambda > 0$ where λ is similar to the costs of raising public funds as in Browning. The social gain generated by water use by farmer i is:

$$\begin{aligned} S'_i(w'_i, h'_i(\theta_i)) &= \pi'_i(w'_i, h'_i(\theta_i)) + (1 - \lambda)gw'_i - gw'_i \\ &= P(-d + bw'_i h'_i - a(w'_i h'_i)^2) - kw'_i - (1 + \lambda)gw'_i - c^t \end{aligned} \quad (2)$$

Expression (2) represents the farmer's profit and the regulator's revenue net of the cost of monitoring and collecting water fees $\lambda gw'_i$. Under full information the regulator's problem is:

$$\max_{w'_i} S'_i(w'_i, h'_i(\theta_i)) \quad \text{s.t.} \quad 0 \leq w'_i \leq \bar{w} - \sum_{l < i} w'_l \quad (3)$$

The interior solution to (3) is:

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

There will be at most one farmer who receives a partial quota, $w_{j_*}^{t*} = \bar{w} - \sum_{i=1}^{j_*-1} w_i^{t*}$, and the remaining $N - j_*$ are left without water, $w_{i>j_*}^{t*} = 0$, the proportion of farmers adopting the modern irrigation technology is $F(\theta^*) - F(\theta^{*z})$ where θ^{*z} solves $\pi_i^H = 0$.

For $\lambda = 0$, water use is given by $w_i^{t0} = \frac{b}{2ah_i^t} - \frac{k + g}{2aP(h_i^t)^2}$ as shown in Dridi. As λ increases water quotas for the senior right holders decrease and some low-type water users could be replaced by users of higher type that had low seniority of right. This water quota reduction could correct the unequal risk sharing due to water scarcity between senior right holders and junior right holder as shown by Burness and Quirk.

WATER RIGHTS ALLOCATION AND TRADING UNDER ASYMMETRIC INFORMATION

We now introduce adverse selection to examine a water allocation scheme when water pricing is not linear and not uniform across users (i.e. second-degree price discrimination), like the type suggested by the U.S. Bureau of Reclamation. We also show that even when there is asymmetric information, water trading could exist and could induce greater technology adoption than otherwise.

Regulated Water Allocation under Adverse Selection

Consider the case the land quality parameter θ_i is unknown to parties other than farmer i . In this setting, 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

task is now to determine a contract consisting of a water quota and a corresponding water fee $\{w_i^{***}(\hat{\theta}_i), \Phi(w_i^{***}(\hat{\theta}_i))\}$ for every parameter $\hat{\theta}_i$. The above contract needs a revelation mechanism.

Let $\Pi(\hat{\theta}_i, \theta_i) = Py(w_i^t(\hat{\theta}_i), \theta_i) - kw_i^t(\hat{\theta}_i) - \Phi(w_i^t(\hat{\theta}_i))$, the profit realized by a farmer i when its true type is θ_i and it announces $\hat{\theta}_i$. The pair $\{w_i^{***}(\hat{\theta}_i), \Phi(w_i^{***}(\hat{\theta}_i))\}$ is a truth-telling mechanism if for every θ_i and $\hat{\theta}_i$ in $[\underline{\theta}, \bar{\theta}]$, the farmers profit when his type is θ_i (resp. $\hat{\theta}_i$) and reveals θ_i (resp. $\hat{\theta}_i$) is greater than his profit when his type is θ_i (resp. $\hat{\theta}_i$) and reveals $\hat{\theta}_i$ (resp. θ_i):

$$Py(w_i^t(\theta_i), \theta_i) - kw_i^t(\theta_i) - \Phi(w_i^t(\theta_i)) \geq Py(w_i^t(\hat{\theta}_i), \theta_i) - kw_i^t(\hat{\theta}_i) - \Phi(w_i^t(\hat{\theta}_i)) \quad (5)$$

and

$$Py(w_i^t(\hat{\theta}_i), \hat{\theta}_i) - kw_i^t(\hat{\theta}_i) - \Phi(w_i^t(\hat{\theta}_i)) \geq Py(w_i^t(\theta_i), \hat{\theta}_i) - kw_i^t(\theta_i) - \Phi(w_i^t(\theta_i)) \quad (6)$$

We show in the appendix that this requires that $w_i^t(\theta_i)$ is a decreasing function of θ_i , and we use that to determine the appropriate level of water fee that makes the pair $\{w_i^{***}(\theta_i), \Phi(w_i^{***}(\theta_i))\}$ an incentive compatible contract. The first-order condition for truth telling (the value of $\hat{\theta}_i$ that maximizes $\Pi(\hat{\theta}_i, \theta_i)$) is:

$$\left. \frac{\partial \Pi(\hat{\theta}_i, \theta_i)}{\partial \hat{\theta}_i} \right|_{\hat{\theta}_i = \theta_i} = 0 \quad (7)$$

To make less burdensome the notation we use a dot on top of the variable to designate the derivative with respect to θ_i . Expression (7) implies:

$$\left[P \left(b h_i^t(\theta_i) - 2 a w_i^t(\theta_i) (h_i^t(\theta_i))^2 \right) - k - \frac{\partial \Phi(w_i^t(\theta_i))}{\partial w_i^t(\theta_i)} \right] \dot{w}_i^t(\theta_i) = 0 \quad (8)$$

If we take $\pi_i^t(w_i^t(\theta_i), h_i^t(\theta_i)) = \Pi(\theta_i, \theta_i)$, then using (8) or the envelope theorem, the total derivative of π_i^t with respect to θ_i is:

$$\dot{\pi}_i^t = P \dot{h}_i^t w_i^t (b - 2 a h_i^t w_i^t) \quad (9)$$

Integrating expressions (9) between $\underline{\theta}$ and θ_i , and equating it to the profit expression in (1), then *ex-post* the optimal water tariff is obtained by a rearrangement:

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

We can therefore state the following proposition.

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

$$\frac{\partial w_i^t(\theta_i)}{\partial \theta_i} \leq 0 \quad (10)$$

and

$$\Phi(w_i^t(\theta_i)) = P y_i(w_i^t(\theta_i), h_i^t(\theta_i)) - k w_i^t(\theta_i) - c^t - \int_{\underline{\theta}}^{\theta_i} \dot{\pi}_i^t(w_i^t(u), h_i^t(u)) du \quad (11)$$

where

$$\dot{\pi}_i^t(w_i^t(u), h_i^t(u)) = P \dot{h}_i^t(u) w_i^t(u) (b - 2 a h_i^t(u) w_i^t(u)), \quad \forall u \in [\underline{\theta}, \theta_i] \quad (12)$$

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 appropriate water fee $\Phi(w_i^{t**}(\theta_i))$. The water fee schedule in (11) 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 a given water quantity. The

properties of the above water schedule 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 (11). A computational illustration in the next section is provided to give additional insights about the shape of the water fee schedule. We now turn to an examination of the water quotas allocated under asymmetric information.

Expressions (10) and (12) form the incentive compatible constraints in the regulator problem. After rearrangement, the social gain function for the i^{th} farmer is:

$$S_i^t(w_i^t, h_i^t(\theta_i)) = (1-\lambda) \left(P(-d + bw_i^t h_i^t(\theta_i) - a(w_i^t h_i^t(\theta_i))^2) - kw_i^t - c^t \right) + \lambda \pi_i^t - gw_i^t \quad (13)$$

In this scenario the regulator's problem is:

$$\max_{w_i^t, \pi_i^t} \int_{\underline{\theta}}^{\bar{\theta}} S_i^t(w_i^t(\theta_i), h_i^t(\theta_i)) f(\theta_i) d\theta_i \quad \text{subject to} \quad (10), (12), \text{ and } \pi_i^t \geq 0 \quad (14)$$

With $\mu(\theta_i)$ the Pontryagin multiplier and considering only constraint (12), we obtain the following Hamiltonian:

$$H(w_i^t, \pi_i^t, \mu) = \left((1-\lambda) \left(P(-d + bw_i^t h_i^t - a(w_i^t h_i^t)^2) - kw_i^t - c^t \right) + \lambda \pi_i^t - gw_i^t \right) f(\theta_i) + \mu(\theta_i) P \dot{h}_i^t w_i^t (b - 2ah_i^t w_i^t) \quad (15)$$

The first-order conditions are:

$$\frac{\partial H}{\partial w_i^t} = f \left((1-\lambda) \left(P(bh_i^t - 2a(h_i^t)^2 w_i^t) - k \right) - g \right) + \mu P \dot{h}_i^t (b - 4ah_i^t w_i^t) = 0 \quad (16)$$

$$-\frac{\partial H}{\partial \pi_i^t} = \dot{\mu} = -\lambda f \quad (17)$$

$$\dot{\pi}_i^t = P \dot{h}_i^t w_i^t (b - 2ah_i^t w_i^t) \quad (18)$$

$$\mu(\bar{\theta}) = 0 \quad (19)$$

$$\pi_i^t(\underline{\theta}) = 0 \quad (20)$$

Integrating (17) between θ_i and $\bar{\theta}$ and using (19) gives:

$$\mu(\theta_i) = \lambda(1 - F(\theta_i)) \quad (21)$$

Replacing $\mu(\theta)$ in (16) by its value from (21) we get the optimal quantity of water:

$$w_i^{t**} = \frac{Pb((1-\lambda)h_i^t + \lambda\dot{h}_i^t R(\theta_i)) - (g + k(1-\lambda))}{2aPh_i^t((1-\lambda)h_i^t + 2\lambda\dot{h}_i^t R(\theta_i))} \quad (22)$$

where $R(\theta_i) = \frac{1 - F(\theta_i)}{f(\theta_i)}$.

Expression (21) shows that the Pontryagin multiplier, $\mu(\theta)$, which represents the marginal contribution of $\pi_i^t(\cdot)$ to $S_i^t(\cdot)$ ranges from λ to zero for all $\theta_i \in [\underline{\theta}, \bar{\theta}]$, this implies that when $\theta_i = \bar{\theta}$ the contribution of $\pi_i^t(\cdot)$ to $S_i^t(\cdot)$ is maximized.

Recall that we solved the model in (14) in its relaxed version without constraints (10) and $\pi_i^t \geq 0$. However, this solution would hold even in the presence of these constraints because from (7) we see that $\dot{\pi}_i^t$ is positive thus, its integral function with respect to θ_i must also be positive. This monotonicity condition may not always be fulfilled, our numerical analysis in the next section shows that it is the case for low values of α_i . Special provisions would be needed to ensure monotonicity (see Laffont and Martimort, p. 141-142), the idea is to find a compromise between two extreme values of the function over the interval where it is non-monotonic and transform the function into a straight line between those two points, this is also known as *bunching* or *pooling*.

In this scenario, with adverse selection, the optimal amount of water is less than the optimal amount of water with full information, $w_i^{***} \leq w_i^{**}$ (see appendix for proof). When an incentive mechanism is designed through a pricing mechanism, water quotas are reduced thus allowing more junior right holders to use water. Because $w_i^{***} \leq w_i^{**}$ one expects a priori to have more retirement of lands of poor quality under this scheme. However, the fact that in equation (20) the optimal control problem we solved grants a zero profit for the farmer whose type is $\underline{\theta}$ ($\pi_i'(\underline{\theta}) = 0$), and the fact that the *ex-post* profit is continuous and strictly increasing⁴ with respect to farmer's type implies the absence of any land retirement at low levels of θ_i . Therefore the proportion of farmers adopting the modern technology is $F(\theta^{**})$. If we wanted to include the possibility of the retirement of poor quality lands, then we would need to start the integration in (12) at a level higher than $\underline{\theta}$. However, truncation of the support $[\underline{\theta}, \bar{\theta}]$ through regulatory holdup is not considered in this study. Therefore, a reduction in water quotas $w_i^{***} \leq w_i^{**}$, increases the number of water users' whose quotas is satisfied but does not induce any retirement of poor quality lands. Since the profit expression in (12) is not analytically tractable, the technology adoption behavior of farmers is analyzed numerically in the next section.

Water Bilateral Trading and Asymmetric Information

We now show that even under adverse selection, water trading is possible and is beneficial to the trading parties and might induce more modern technology adoption. Our concern is to establish the conditions under which water trading occurs and to appraise the

⁴ See equation (18) and consider the X-efficiency condition.

volume of trade. Based on the realized level of trades we explore the nature 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 $\pi_i^{t**}(w_i^{t**}, h_i^t(\theta_i))$ and $\pi_j^{t**}(w_j^{t**}, h_j^t(\theta_j))$. Agents whose type is below θ^{**} adopt the modern irrigation technology while agents whose type is above θ^{**} adopt the modern technology. The reservation levels of profits will be taken from the previous model based on the determined water quota and the choice of irrigation technology. We implicitly assume that disinvestment is not possible, indeed while equipment can be sold investments made to learn how to use it are not recoverable, therefore once the modern technology is acquired it cannot be abandoned.

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

$$\pi_i^t(x_{ij}, h_i^t) = P\left(-d + bh_i^t(w_i^{t**} - x_{ij}) - a\left(h_i^t(w_i^{t**} - x_{ij})\right)^2\right) - k(w_i^{t**} - x_{ij}) - c^t - \Phi(w_i^{t**}) + m_{ji}(x_{ij}) \quad (23)$$

$$\pi_j^t(x_{ij}, h_j^t) = P\left(-d + bh_j^t(w_j^{t**} + x_{ij}) - a\left(h_j^t(w_j^{t**} + x_{ij})\right)^2\right) - k(w_j^{t**} + x_{ij}) - c^t - \Phi(w_j^{t**}) - m_{ji}(x_{ij}) \quad (24)$$

We consider the existence of a benevolent broker or a facilitator, like 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 not limited to satisfying the equality of marginal profits across the two

trading farmers. Consider the direct revelation mechanism where agents i and j reveal their types to the broker.

Let $\Pi_i(x_{ij}(\hat{\theta}_i, \theta_j), h'_i(\theta_i))$ 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 $\Pi_j(x_{ij}(\theta_i, \hat{\theta}_j), h'_j(\theta_j))$. The broker's problem is to maximize the ex-post expected sum of profits:

$$\max_{x_{ij}(\cdot)} E_{\theta_i} E_{\theta_j} (\Pi_i(\cdot) + \Pi_j(\cdot)) \quad (25)$$

such that;

$$E_{\theta_j} \Pi_i(x_{ij}(\theta_i, \theta_j), h'_i(\theta_i)) \geq E_{\theta_j} \Pi_i(x_{ij}(\hat{\theta}_i, \theta_j), h'_i(\theta_i)) \quad (26)$$

$$E_{\theta_i} \Pi_j(x_{ij}(\theta_i, \theta_j), h'_j(\theta_j)) \geq E_{\theta_i} \Pi_j(x_{ij}(\theta_i, \hat{\theta}_j), h'_j(\theta_j)) \quad (27)$$

$$\pi_i^t(x_{ij}(\theta_i, \theta_j), h'_i(\theta_i)) \geq \pi_i^{t**}(w_i^{t**}, h'_i(\theta_i)) \quad (28)$$

$$\pi_j^t(x_{ij}(\theta_i, \theta_j), h'_j(\theta_j)) \geq \pi_j^{t**}(w_j^{t**}, h'_j(\theta_j)) \quad (29)$$

$$0 \leq x_{ij}(\theta_i, \theta_j) \leq w_i^{t**} \quad (30)$$

Constraints (26) and (27) are incentive compatibility constraints that ensure truth telling by farmers i and j , while constraint (30) limits the volume of trade to the endowments of the seller. Constraints (28) and (29) grant the trading parties a minimum level of profit equal to the profit they had before initiating any water trading. Here we consider *ex-post* individual rationality, which as Gresik stated is a much stronger requirement than the *interim* individual rationality requirement found in a large number of studies. Indeed the standard in mechanism design is interim individual rationality, where the constraints (28) and (29) are replaced by their expected values.

We start solving the problem described by (25)-(30), by considering only the incentive compatible constraints to rewrite the objective function (25) into a sum of expected profits that are incentive compatible.

For farmer i , truth-telling implies:

$$\left. \frac{\partial E_{\hat{\theta}_j} \Pi_i \left(x_{ij}(\hat{\theta}_i, \theta_j), h_i^t(\theta_i) \right)}{\partial \hat{\theta}_i} \right|_{\hat{\theta}_i = \theta_i} = 0 \quad (31)$$

Using the envelope theorem or considering (31), the total derivative of $\Pi_i \left(x_{ij}(\theta_i, \theta_j), h_i^t(\theta_i) \right)$ with respect to θ_i is:

$$\begin{aligned} \frac{dE_{\theta_j} \Pi_i(\cdot)}{d\theta_i} &= \frac{\partial E_{\hat{\theta}_j} \Pi_i(\cdot)}{\partial h_i^t(\cdot)} \frac{\partial h_i^t(\cdot)}{\partial \theta_i} \\ &= \int_{\underline{\theta}}^{\bar{\theta}} P \left(b(w_i^{t**} - x_{ij}(\theta_i, \theta_j)) \dot{h}_i^t(\theta_i) - 2a(w_i^{t**} - x_{ij}(\theta_i, \theta_j))^2 h_i^t(\theta_i) \dot{h}_i^t(\theta_i) \right) f(\theta_j) d\theta_j \end{aligned} \quad (32)$$

An agent i whose type is $\bar{\theta}$, does not enter into a trade because no other agent j can have a marginal profit that is higher than agent i 's, thus $\Pi_i \left(x_{ij}(\bar{\theta}, \theta_j), h^t(\bar{\theta}) \right) = \pi_i^{t**} \left(w_i^{t**}(\bar{\theta}), h^t(\bar{\theta}) \right) = \bar{\pi}_i$, which is a constant. Indeed an agent whose type is $\bar{\theta}$ has the lowest quantity of water by virtue of assumption 3 along with the highest productivity, as a result the agent's marginal valuation for water is the highest and no other agent can compensate him for reducing water use. From (32) the incentive compatible profit is rewritten as:

$$E_{\theta_j} \Pi_i(\cdot) = \bar{\pi}_i - \int_{\theta_i}^{\bar{\theta}} \int_{\underline{\theta}}^{\bar{\theta}} P \left(b(w_i^{t**} - x_{ij}(\cdot)) \dot{h}_i^t(u) - 2a(w_i^{t**} - x_{ij}(\cdot))^2 h_i^t(u) \dot{h}_i^t(u) \right) f(\theta_j) d\theta_j du \quad (33)$$

In order to get the first part of (25), we compute the expected profit of farmer i , and using Fubini's theorem we get:

$$E_{\theta, \theta_j} \Pi_i(\cdot) = \bar{\pi}_i - \int_{\underline{\theta}}^{\bar{\theta}} \int_{\underline{\theta}}^{\bar{\theta}} \int_{\underline{\theta}}^{\bar{\theta}} P(w_i^{t**} - x_{ij}(\cdot)) \dot{h}_i(u) (b - 2a(w_i^{t**} - x_{ij}(\cdot)) h_i'(u)) f(\theta_j) f(\theta_i) du d\theta_j d\theta_i \quad (34)$$

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 (20) in the previous section. A similar procedure to (31) through (34), gives:

$$E_{\theta, \theta_i} \Pi_j(\cdot) = \int_{\underline{\theta}}^{\bar{\theta}} \int_{\underline{\theta}}^{\bar{\theta}} \int_{\underline{\theta}}^{\bar{\theta}} P(w_j^{t**} + x_{ij}(\cdot)) \dot{h}_j(u) (b - 2a(w_j^{t**} + x_{ij}(\cdot)) h_j'(u)) f(\theta_i) f(\theta_j) du d\theta_i d\theta_j \quad (35)$$

Expressions (34) and (35) transform the broker's problem to maximizing the sum of expected profits with respect to the optimal amount of water transfer $x_{ij}(\theta_i, \theta_j)$ that must be accompanied by a monetary transfer of $m_{ji}(x_{ij})$ satisfying the constraints (28)-(30).

In (34), observe that in addition to $\bar{\pi}_i$, which is fixed, there is an additional quantity that represents the expected value of output forgone by i and gained by j , upon the transfer of $x_{ij}(\theta_i, \theta_j)$ units of water. It is the later quantity that the broker has to maximize. If we assume the absence of transaction costs related to water trading, then there will be no trace of the monetary transfer, $m_{ji}(x_{ij})$ in (34). Applying Liebnitz's rule and after simplification the maximization of the sum of (34) and (35) with respect to $x_{ij}(\theta_i, \theta_j)$ reduces to the following first order condition:

$$\int_{\underline{\theta}}^{\theta_j} \dot{h}_j'(u) (b - 4a(w_j^{t**} + x_{ij}(\theta_i, u)) h_j'(u)) du = \int_{\theta_i}^{\bar{\theta}} \dot{h}_i'(u) (-b + 4a(w_i^{t**} - x_{ij}(u, \theta_j)) h_i'(u)) du \quad (36)$$

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 $x_{ij}(\theta_i, \theta_j)$:

$$h'_j(\theta_j)h'_j(\theta_j)\frac{\partial x_{ij}(\cdot)}{\partial \theta_i} + h'_i(\theta_i)h'_i(\theta_i)\frac{\partial x_{ij}(\cdot)}{\partial \theta_j} = 0 \quad (37)$$

This far, when we introduced adverse selection we assumed that farmer i is the seller and that farmer j is the buyer. Let us assume now that $x_{ij}(\cdot)$ is negative and in (37) substitute $x_{ij}(\cdot)$ by $-x_{ji}(\cdot)$ we get after simplification the same expression as in (37). This shows that regardless of the way we setup the trading problem the trading rule derived in (37) is the same. Otherwise stated, if the broker does not know the true valuations of any two agents and if, the two agents are willing to purchase or sell with profit a quantity of an item they each individually own, then designating one agent as buyer and the other as seller is irrelevant. The following proposition summarizes the above result.

Proposition 2: Consider a social gain maximizing broker and two agents i and j with initial endowments w_i and w_j in a given good and private valuations for the good. Then 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 who acts as the Walrasian auctioneer whose sole role is to match the buyers and the sellers without seeking gains from the transaction can bring about mutually beneficial agreements between buyers and sellers. The broker can be an intermediary who due to the existence of adverse selection realizes a gain from bringing the buyers and the sellers to an

agreement (Spulber). It is important that the broker be different from the water authority that assigns the initial endowments in water. Unless the relation between the farmers and the regulator is changed, the broker cannot improve upon the outcome of the previous subsection. This is mainly because the quantities $w_i^{***}(\theta_i)$ and $\Phi(w_i^{***}(\theta_i))$ from the previous subsection, are considered constants by the broker, thus excluding any revision or 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 $\frac{1}{2}\left(\frac{\theta_i - \underline{\theta}}{\bar{\theta} - \underline{\theta}}\right)^{2\alpha_i}$ and for $h^t(\theta_j)\dot{h}^t(\theta_j)$ it is $\frac{1}{2}\left(\frac{\theta_j - \underline{\theta}}{\bar{\theta} - \underline{\theta}}\right)^{2\alpha_j}$. With C_0 and C_1 being constants, the general solution for (37)

is then obtained as follows:

$$x_{ij}(\theta_i, \theta_j) = C_0 \cdot \left(\frac{2}{2\alpha_j + 1} (\bar{\theta} - \underline{\theta})^{2\alpha_i} (\theta_j - \underline{\theta})^{2\alpha_j + 1} - \frac{2}{2\alpha_i + 1} (\bar{\theta} - \underline{\theta})^{2\alpha_j} (\theta_i - \underline{\theta})^{2\alpha_i + 1} \right) + C_1 \quad (38)$$

Expression (38) can be checked to be a general solution to (37) where no trade occurs if farmers were identical, in which case $C_1 = 0$. The constant C_0 is a scaling factor that can be determined such that:

$$C_0(i, j) = \frac{\max\{w_i^{***}; \forall i\}}{\max\{K(\theta_i, \theta_j); \forall (i, j)\}} \quad (39)$$

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

Now that the optimal water trading rule is determined, we need to direct our attention to the rest of the constraints of the broker's problem, namely constraints (28)-(30). If we denote by

x_{ij}^M the optimal level of water trading, for that level to be feasible it has to satisfy the constraints below for the monetary transfer, its final level will be determined through negotiation between the trading parties:

$$m_{ji}(x_{ij}) \geq \pi_i^{t**} - P \left(-d + bh^t(\theta_i)(w_i^{t**} - x_{ij}) - a \left(h^t(\theta_i)(w_i^{t**} - x_{ij}) \right)^2 \right) + k(w_i^{t**} - x_{ij}) + c^t + \Phi_i^{**} \quad (40)$$

$$m_{ji}(x_{ij}) \leq P \left(-d + bh^t(\theta_j)(w_j^{t**} + x_{ij}) - a \left(h^t(\theta_j)(w_j^{t**} + x_{ij}) \right)^2 \right) - k(w_j^{t**} + x_{ij}) - c^t - \Phi_j^{**} - \pi_j^{t**} \quad (41)$$

Since the water quotas determined by the regulator in the previous subsection are decreasing across farmers' types then 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 it has to be from the lower type to the higher type farmers. This means that at the egress of the trade some of the farmers who sell part of their water quota will adopt the modern technology otherwise the trade will only increase their profits through the revenue of water sales. The adoption of the modern technology is feasible under the following condition:

$$P(w_i^{L**} - x_{ij})(h_i^H(\theta_i) - h_i^L(\theta_i)) \left[b - a(w_i^{L**} - x_{ij})(h_i^H(\theta_i) + h_i^L(\theta_i)) \right] \geq c^H \quad (42)$$

The current section dealt with water use and technology adoption under adverse selection. We showed that the existence of adverse selection makes water regulation inefficient even if a nonlinear pricing scheme is devised. At this point, the problem with the regulation is the absence of retirement by unproductive lands. As a remedy to those inefficiencies, we suggested the use of water trading and devised a trading rule that is incentive compatible. If condition (42) 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. Based on the results of various studies showing substantial gains from water trading compared to its transaction costs (Easter), we overlooked the existence of transaction costs related to the trade. In the following section, we apply the results found above to a numerical illustration from the literature, which will bring additional insights that we were not able to uncover analytically.

NUMERICAL ILLUSTRATION AND ADDITIONAL INSIGHTS

To illustrate the findings of the previous sections and to have additional insights and results that could not be provided analytically, we use a numerical illustration. Based on data from southern California and Arizona for fruits and vegetables production, Caswell and Zilberman construct a quadratic production function with the following coefficients $d=-6$, $b=10.68$, and $a=1.7$, the production function measures the output per acre. Output price is assumed by the authors to be \$100 per unit of output. The additional setup costs required to adopt the modern technology are between \$50 and \$100 per acre; we use the value of $c^H = \$75$ 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 reported that in the western United States when $\theta_i = 0.6$ the effectiveness of the modern technology (drip) is 0.95, $h^H(0.6) = 0.95$, implying $\alpha_i = 0.100413$, that we round to $\alpha_i = 0.1, \forall i$ ⁵. We use a value of $k=15$ for the private cost supported by the farmer to use water, to cover the cost of the energy to pump water from its source to the field as in Caswell and Zilberman, where water is pumped from a well. We assume also that farmers are charged $g=\$80$

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

per acre-foot of water. The average social cost per dollar of water fee collected is reported by Boyer and Laffont (p.140) to be $\lambda = 0.3$ in developed economies. The farmers' type, θ_i , is defined over the support $[0,10]$, and has a density $f(\theta_i) = \frac{z(\theta_i)}{Z(\bar{\theta}) - Z(\underline{\theta})}$, where z is a Gaussian distribution with mean $\frac{\bar{\theta} + \underline{\theta}}{2}$ and variance 1, and Z its cumulative distribution.

When water use is regulated, water quotas are determined by water authorities in a social gain maximizing fashion; we showed analytically that the water quota is less than the quantity of water that would maximize the farmer's profit. Figure 1.b, depicts the profit functions under full information, and it shows the critical value of farmer's type ($\theta^* = 7.66$) below which the modern technology is adopted and above which the traditional technology is maintained. In figure 1.b, we do not see any retirement of poor quality lands, this is due to the use of $\alpha = 0.1$ to comply with the data, in fact for higher values of α lands retirement does exist as implied analytically. Figure 1.d shows the social gain functions and it indicates, as expected, that the threshold level for switching technology is at a higher level than the level selected by the farmer in figure 1.b. As we stated earlier assumption 3 does not affect the analysis of the technology adoption because the increasing portion of water quota for the low technology users falls in the area where the modern technology is being used, therefore it is irrelevant.

<< insert figure 1 here >>

The numerical analysis for the adverse selection case is slightly more intricate than in the case of full information. The difficulty arises from the shape of the optimal water quota found in equation (22) that, as shown in proposition 2, needs to be monotone decreasing. Figure 1.a

depicts the optimal water quantity for every type of land quality under conditions of adverse selection, where one notices that while monotonic decreasing, it approaches extremely high values for lower types. This, a priori should not be a problem except that it violates assumption 1, the only case where the use of infinite amounts of water is viable to the farmers is when water use is subsidized⁶. In order to maintain monotonicity and avoid subsidies, we impose a cap on water rights, if the water quota found in (22) is larger than the water quota found in (4), then the water quota is set to zero otherwise it is the water quota found in (22) that prevails. Regarding the case of water quota when the modern technology is adopted, a rough way to correct for that is to make it monotonic to become as depicted with the thick lines in figure 1.a, by trial and error we found that when $\theta \leq 4.06$, the water quota needs to be set at a value of about 2.93 units.

The use of water quotas as depicted in figure 1.a allows for the computation of the incentive compatible profits for every farmer's type in (12). In order to compute the integral

function we use the summed quadrature formula, $\int_a^b f(t)dt = \lim_{dt \rightarrow 0} \sum_{n=0}^{\frac{b-a}{dt}} (f(a + ndt).dt)$, the step size

we use is $dt = 1/1000$.

Using the above quadrature formula, the incentive compatible profits are plotted in figure 1.b, the threshold level for technology switching is located at a much lower level ($\theta^{**} = 5.22$) than under full information. The introduction of adverse selection reduces significantly the adoption of modern technology and suppresses poor land quality retirement since farmers of all types are granted a minimum level of profit equal to zero. 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.

⁶ With subsidy, all farmers' types will use only the traditional technology.

Doing so might lower significantly 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 by the regulator, because what should have been done is the retirement of low quality lands.

In principal-agent models, it is expected that the social gain obtained under adverse selection is always lower than the social gain under full information. The fact that we obtained larger social gain under adverse selection when $t = L$, might seem surprising at first since the model under adverse selection is more constrained than under full information, however the fact that the pricing method is different across the two scenarios makes the result reasonable. Under full information, the pricing schedule was linear whereas under adverse selection the pricing schedule was nonlinear and discriminative. From figure 1.c, it can be seen that over a large portion of $[\underline{\theta}, \bar{\theta}]$, the water fee paid under adverse selection is always higher than the one under full information when $t = H$. In contrast, the water fee paid under adverse selection is always less than the water fee paid under full information when $t = L$, which in part explains the low level of technology adoption when adverse selection is considered. The water fee under adverse selection is decreasing over farmer's type and it is lower for farmers who adopt the traditional technology ($t = L$), to become zero at $\bar{\theta}$.

So far we found that the introduction of adverse selection and the use of nonlinear and discriminative water pricing although leading to an even lower level of water quotas eliminates the retirement of poor quality lands and induces a lower level of technology adoption. The reduction in technology adoption is because low water fee when $t = L$ attracts some farmers to keep the traditional technology rather than switch to the modern technology ($t = H$). Many economists view nonlinear discriminative pricing as an efficient pricing method. However, the

introduction of adverse selection seems to produce distortions that a move toward water trading might lessen.

<< insert figure 2 here >>

Considering the level $\theta^{**} = 5.22$ (figure 1.b) at which farmers switch their level of technology we can plot in a three-dimensional space the result found in (38), the solution surface is depicted in figure 2.a. A first look at figure 2.a shows that across the line $\theta_i = \theta_j$, where $x_{ij}(\theta_i, \theta_j = \theta_i) = 0$, there is opposition of signs in the volume of trade, figure 2.a shows also that highest possible, not necessarily feasible, trading occur when $(\theta_i, \theta_j) \in [\theta^{**}, \bar{\theta}]^2$.

In figure 2.b, we provide a contour plot of potential trade levels and a highlight of all combinations of (θ_i, θ_j) 's that allow for the adoption of modern irrigation technology, if the corresponding water deals for farmer i to farmer j are realized. The modern irrigation technology is adopted when the net gains of technology adoption is higher than the cost of adoption as depicted in condition (42).

Figure 2.c displays a contour plot of potential water trades with a highlight of the feasible levels of trade leading to the adoption of the modern technology $((\theta_i, \theta_j) \in [\theta^{**}, \bar{\theta}]^2)$ and those of lower level that do not lead to the adoption of the modern technology $((\theta_i, \theta_j) \notin [\theta^{**}, \bar{\theta}]^2)$ as they are only minor adjustment of water use across farmers. This shows that monetary transfers do exist to support feasible trade volumes determined by the trading rule in (38). The flows of trade seem to meet the intuition that farmers with high valuations for water will be water buyers and farmers with low valuation for water will be water sellers

The above analysis gives an idea about the possible levels of trade that farmers of different types can realize and their technology adoption implication. Since the final level of monetary transfer is determined through negotiation between the seller and the buyer then it is not possible to provide its final level. Nevertheless, for various potential water trade levels inducing modern technology adoption could be represented in a contour plot (4.d), where we can see that certain water volumes can be traded for up to more or less \$50.

CONCLUSION

This paper shows that under adverse selection, water trading among farmers can reduce the distortion created in allocation of water quotas relative to the situation with full information. Adverse selection introduces inefficiencies and distortions because it induces less technology adoption and reduces incentives to retire low quality lands. We showed that trade occurs for two reasons. First, it occurs amongst low type farmers who have already adopted the modern irrigation technology and second, it occurs between farmers who did not adopt the modern irrigation technology, water is transferred from low type farmers to higher type farmers, and in some cases the revenues of water transfer allows for the adoption of the modern technology.

The results of the numerical analysis showed also that the existence of a second phase of trading after the regulator initially allocates the water quotas generates important gains and induces additional technology adoption that the initial allocation of water resources could not achieve alone.

In developing the model in this paper, we considered only one-shot games and excluded contract renegotiation. In the context of water rights this assumption is not really restrictive since water rights usually span over a long period, therefore each time the contract is designed past information is of little relevance. The pricing of resources under adverse selection can bring

insights to the water allocation problem as in many countries the main reason for inefficiency comes from the pricing scheme used that for various reasons often leads to an under-pricing of water. A better alternative to pricing would be auction of water rights instead of the determination of water quotas by the regulator, and the possibility of having a second market to correct for any inefficient allocation of water rights. Water auctions have been used recently 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, in addition the implementation of water auctions seems to be more suitable for new water resources where no previous rights could be claimed unlike in this paper where prior appropriation rights on water are assumed to exist.

APPENDIX

Incentive compatible contract

Let $\Pi(\hat{\theta}_i, \theta_i) = Py(w'_i(\hat{\theta}_i), \theta_i) - kw'_i(\hat{\theta}_i) - \Phi(w'_i(\hat{\theta}_i))$, the profit realized by a farmer i when its true type is θ_i and it announces $\hat{\theta}_i$. The pair $\{w_i^{**}(\hat{\theta}_i), \Phi(w_i^{**}(\hat{\theta}_i))\}$ is a truth-telling mechanism if for every θ_i and $\hat{\theta}_i$ in $[\underline{\theta}, \bar{\theta}]$, the farmers profit when his type is θ_i (resp. $\hat{\theta}_i$) and reveals θ_i (resp. $\hat{\theta}_i$) is greater than his profit when his type is θ_i (resp. $\hat{\theta}_i$) and reveals $\hat{\theta}_i$ (resp. θ_i):

$$Py(w'_i(\theta_i), \theta_i) - kw'_i(\theta_i) - \Phi(w'_i(\theta_i)) \geq Py(w'_i(\hat{\theta}_i), \theta_i) - kw'_i(\hat{\theta}_i) - \Phi(w'_i(\hat{\theta}_i)) \quad (43)$$

and

$$Py(w'_i(\hat{\theta}_i), \hat{\theta}_i) - kw'_i(\hat{\theta}_i) - \Phi(w'_i(\hat{\theta}_i)) \geq Py(w'_i(\theta_i), \hat{\theta}_i) - kw'_i(\theta_i) - \Phi(w'_i(\theta_i)) \quad (44)$$

Setting $w = w'_i(\theta_i)$ and $\hat{w} = w'_i(\hat{\theta}_i)$ and dropping the indices i and t and using u as integration variable then (43) and (44) imply (Laffont and Martimort, p.134-140):

$$-\int_{\hat{w}}^w \left(P \frac{\partial y(u, \theta)}{\partial u} - ku - \frac{\partial \Phi(u)}{\partial u} \right) du \leq 0 \quad (45)$$

and

$$\int_{\hat{w}}^w \left(P \frac{\partial y(u, \hat{\theta})}{\partial u} - ku - \frac{\partial \Phi(u)}{\partial u} \right) du \leq 0 \quad (46)$$

Using v as integration variable and adding (45) to (46) we get:

$$\int_{\theta}^{\hat{\theta}} \int_{\hat{w}}^w P \frac{\partial^2 y(u, v)}{\partial u \partial v} dudv \leq 0 \quad (47)$$

Recall that $\frac{\partial^2 y(w'_i(\theta_i), \theta_i)}{\partial w'_i(\theta_i) \partial \theta_i} = \frac{\partial h'_i(\theta_i)}{\partial \theta_i} (b - 4ah'_i(\theta_i)w'_i(\theta_i))$ and that by assumption 3 we

have $w'_i > \frac{b}{4ah'_i(\theta_i)}$, therefore $\frac{\partial^2 y(w'_i(\theta_i), \theta_i)}{\partial w'_i(\theta_i) \partial \theta_i} < 0$ and $w'_i(\theta_i)$ is a decreasing function of θ_i .

The relation between $w'_i(\theta_i)$ and θ_i being established, we now determine the appropriate level of water fee that makes the pair $\{w_i^{**}(\theta_i), \Phi(w_i^{**}(\theta_i))\}$ an incentive compatible contract.

The first-order condition for truth telling (the value of $\hat{\theta}_i$ that maximizes $\Pi(\hat{\theta}_i, \theta_i)$) is:

$$\left. \frac{\partial \Pi(\hat{\theta}_i, \theta_i)}{\partial \hat{\theta}_i} \right|_{\hat{\theta}_i = \theta_i} = 0 \quad (48)$$

To make less burdensome the notation we use a dot on top of the variable to designate the derivative with respect to θ_i . Expression (48) implies:

$$\left[P \left(bh'_i(\theta_i) - 2aw'_i(\theta_i)(h'_i(\theta_i))^2 \right) - k - \frac{\partial \Phi(w'_i(\theta_i))}{\partial w'_i(\theta_i)} \right] \dot{w}'_i(\theta_i) = 0 \quad (49)$$

If we take $\pi_i^t(w_i^t(\theta_i), h_i^t(\theta_i)) = \Pi(\theta_i, \theta_i)$, then using (49) or the envelope theorem, the total derivative of π_i^t with respect to θ_i is:

$$\dot{\pi}_i^t = Ph_i^t w_i^t (b - 2ah_i^t w_i^t) \quad (50)$$

Integrating expressions (50) between $\underline{\theta}$ and θ_i , and equating it to the profit expression in (1), then *ex-post* the optimal water tariff is obtained by a rearrangement:

$$\Phi(w_i^t) = Py_i(w_i^t, h_i^t(\theta_i)) - kw_i^t - c^t - \int_{\underline{\theta}}^{\theta_i} \dot{\pi}_i^t(w_i^t(u), h_i^t(u)) du \quad (51)$$

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*} .

$$\frac{Pb((1-\lambda)h^t + \lambda h^t R(\theta_i)) - (g + k(1-\lambda))}{2aPh^t((1-\lambda)h^t + 2\lambda h^t R(\theta_i))} \leq \frac{b}{2ah^t(\theta_i)} - \frac{k + g(1+\lambda)}{2aP(h^t(\theta_i))^2} \quad (52)$$

A simplification and rearrangement of (52) gives:

$$0 \leq gh\lambda^2 + \lambda h^t R(\theta_i)(Pbh^t - 2k - 2g(1+\lambda)) \quad (53)$$

Recall that $w_i^{t*} = \frac{b}{2ah^t(\theta_i)} - \frac{k + g(1+\lambda)}{2aP(h^t(\theta_i))^2}$ and considering assumption 3 we get:

$$\frac{b}{4ah^t(\theta_i)} - \frac{k + g(1+\lambda)}{2aP(h^t(\theta_i))^2} > 0 \quad (54)$$

Expression (54) implies that $Pbh^t - 2k - 2g(1+\lambda) > 0$, which means that expression (53) is indeed positive; therefore, the water quota under adverse selection is less than the water quota under full information, $w_i^{t**} < w_i^{t*}$.

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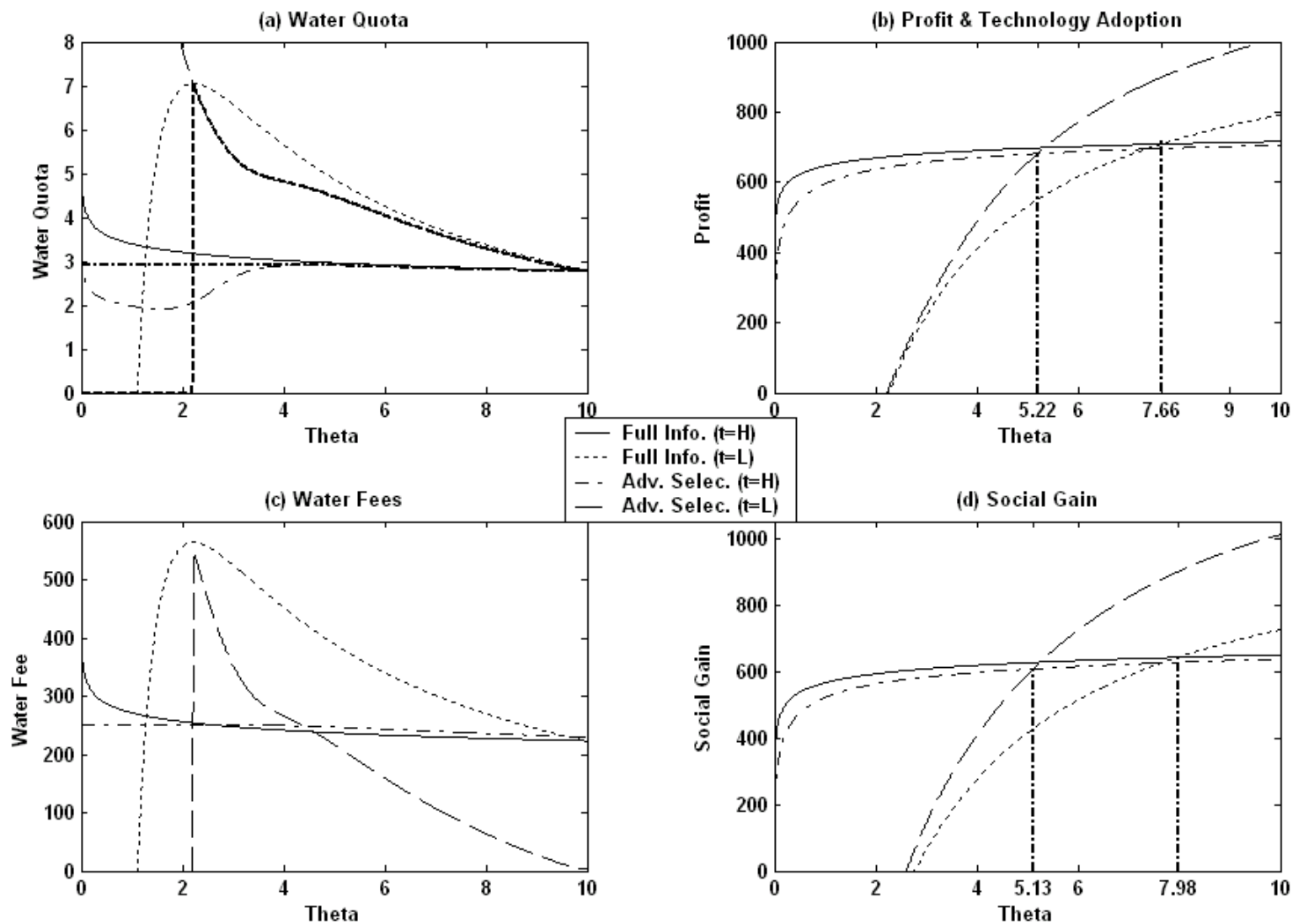


FIGURE 1: Water quotas and fees, profits, and social gains under full information and adverse selection

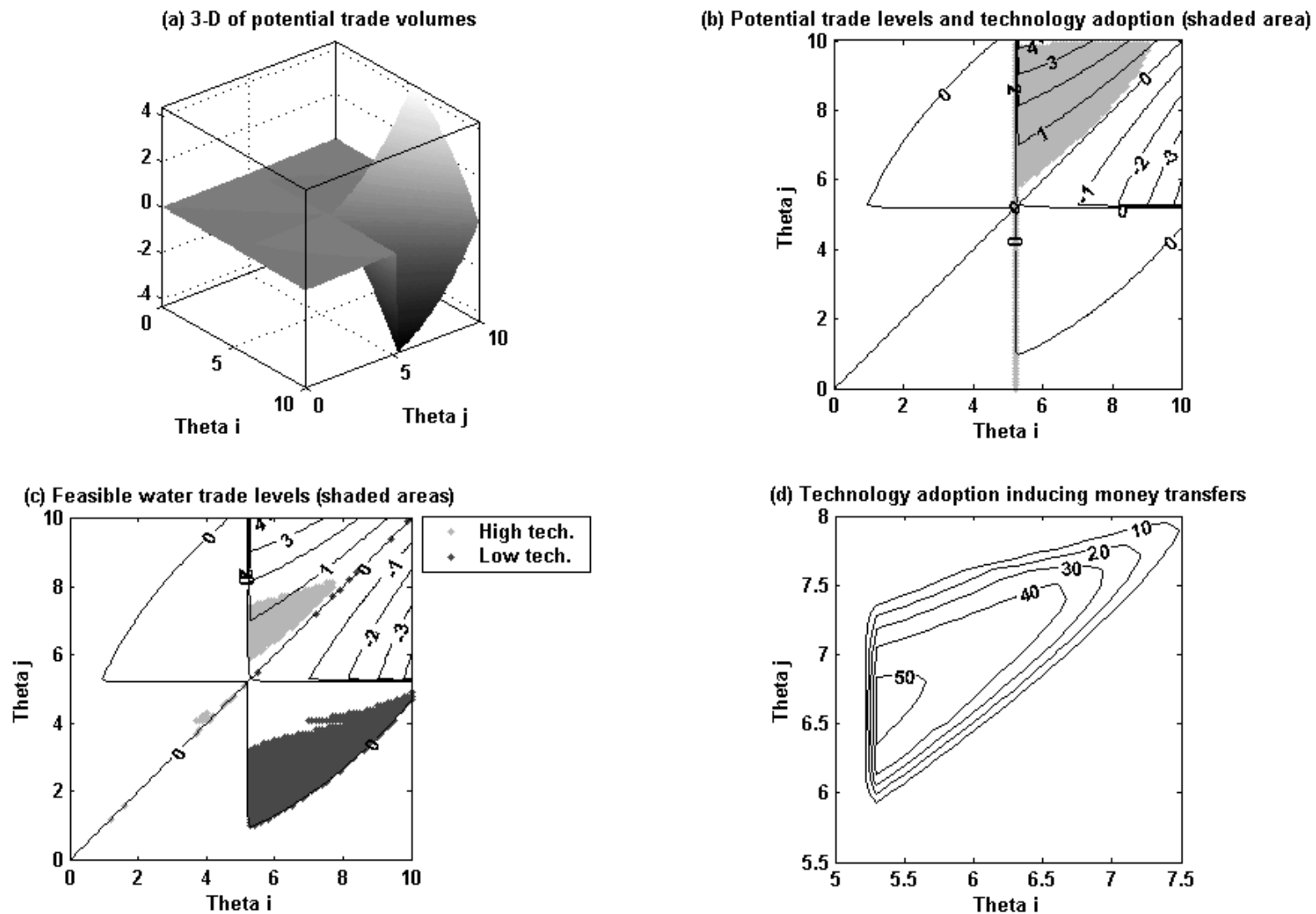


Figure 2: Water trading and technology adoption feasibility