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SESSION VI: AGRICULTURAL POLICY AND SUSTAINABLE DEVELOPMENT - II

PAPER 2: ASYMMETRIC INFORMATION AND THE PRICING OF NATURAL RESOURCES: THE CASE OF UNMETERED WATER

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Asymmetric Information and the Pricing of Natural Resources:

The Case of Unmetered Water

Rodney B. W. Smith and Yacov Tsur

Abstract

This paper uses mechanism design theory to (i) propose a mechanism to price irrigation water when farmers are heterogeneous in their production technologies (adverse selection) and their individual water uses are unobserved (moral hazard) and (ii) discusses briefly when such a mechanism might be economically unreasonable. Unmetered irrigation water is often priced by imposing per-acre fees on cultivated acreage or by charging per-unit fees on observable inputs or outputs. The offered pricing procedure is based on the observed output and achieves a first-best outcome when implementation is free of transaction costs.

1. Introduction

Throughout the world, volumetric pricing of irrigation water – where water is priced based on the quantity (volume) of water used – is the exception rather than the rule (Boss and Walters, 1990), the reason being that irrigation water is often unmetered. Riparian rights, under which farmers divert water freely from a nearby stream or pump water from an underlying aquifer, are pervasive. Unmetered water is typically priced on a per area basis; where a fixed, prespecified amount is paid for any cultivated hectare, or by taxing observable outputs or inputs (Bowen and Young, 1986, p. 211; Tsur and Dinar, 1995), or they are ignored altogether. From the farmers' perspective, per-hectare water fees represent fixed costs and do not affect per-hectare water input decisions. Pricing water indirectly through observed instruments like outputs and/or other inputs may affect water allocation decisions. However, unless such a pricing mechanism makes use of all available information concerning production technologies, such instruments will likely be inaccurate proxies for water use and the indirect water fees may be off target and could even increase inefficiencies. This is likely to occur when individual farmers are heterogeneous in their production technologies and a single per unit output tax is imposed.

If the entire cost of water supply is borne by the water users, then it makes no difference if water inputs are unobservable: the farmers themselves take into account the true cost of water in their input/output decisions. A problem arises when the costs of water includes non-private components due to scarcity and extraction cost externalities: declining water tables lead to higher pumping costs in the future (temporal externality); costs of water supplied by a large-scale irrigation project include costs borne by the water authority such as conveyance costs from the water source to farmers' fields, maintenance and operation costs, and (imputed) investment costs. Another common situation is that of many users pumping groundwater from a shared aquifer via private wells (spatial cost externality).

When individual water use is observable, it is (in principle) straightforward to include such costs in the price of water. The situation is more complicated when (i) water is unmetered and individual users' applications cannot be observed (moral hazard) and (ii) farmers differ in their production technologies and these technologies are private information, i.e., known to the farmer but not to the water authority (adverse selection). Further complications arise when regulation entails transaction costs associated with administration, monitoring and enforcing activities.

For the situation described by (i) and (ii), we offer in this paper a water pricing scheme that depends only on observable outputs. In the absence of implementation (transaction) costs, the pricing procedure achieves first-best allocations: i.e., the optimal allocation when individual water applications are observed. With transaction costs, first-best allocations are not possible and second-best allocations might be attainable. Results in the numerical example suggest that transaction costs might possibly explain the types of water pricing institutions currently observed.

The idea underlying the pricing procedure is rather straightforward. If the regulator had complete information on the relevant parameters of farmers' production technologies, she could infer each farmer's water use from his (observed) output and the situation would then be as if water use were observed. Lacking complete information about farmers' production technologies, the regulator conditions her actions (the pricing mechanism) on the farmers' unobservable technologies. She does this by appropriately imposing (nonlinear) taxes on outputs. Our procedure follows closely the direct revelation mechanism approach found of Guesnerie and Laffont (1984), and Laffont and Tirole (1987).

The next section formalizes the problem. Section 3 describes the pricing mechanism. Section 4 offers a numerical example and Section 5 concludes.

2. The Problem

Farmers: Consider n farmers – indexed $i = 1,2,\ldots,n$ – producing a homogeneous crop y using water as an input. Farmers' water response functions (after maximizing out all variable inputs other than water) are

$$Y^i = g(w^i, \beta^i),\ i = 1,2,\ldots,n,$$

where $g(\cdot\cdot)$ is the water response function, w is water input and $\beta^i \in [0,1]$ is a parameter signifying the farmer's *type*. β^i is a scalar index of variables like farming ability or soil quality. The water response function is assumed thrice continuously differentiable in both arguments, increasing and strictly concave in w, strictly increasing in β^i, with $g_{12}=\partial^2 g/\partial w \partial\beta^i \geq 0$ (subscripts denote partial derivatives).

For a given β^i, g can be inverted to give:

$$w^i = W(Y^i, \beta^i),$$

i.e., $W(\cdot\cdot)$ satisfies $W(g(w, \beta^i), \beta^i) = w$. The properties of $g(\cdot\cdot)$ imply[1]

$$(1) \qquad W_1 \equiv \frac{\partial W}{\partial Y} > 0; \quad W_{11} \equiv \frac{\partial^2 W}{\partial Y^2} > 0; \quad \frac{\partial W}{\partial \beta} \equiv W_2 < 0; \quad \frac{\partial^2 W}{\partial Y \partial \beta} \equiv W_{12} \leq 0.$$

Let c represent the per unit cost of water borne by each farmer. The parameter c may represent the cost of delivering water from the gates of an irrigation canal or a stream flow to the fields, or it may measure the cost of pumping water from an underlying aquifer. In the absence of regulation, farmers' profits are

$$p\,Y^i - cW(Y^i, \beta^i), \qquad i = 1,2,\ldots,n,$$

and profit seeking farmers produce $y(p,c,\beta^i)$ units of output, satisfying

$$p - cW_1(Y^i(p,c,\beta^i),\beta^i) = 0$$

and use $W(Y^i(p,c,\beta^i),\beta^i)$ units of water .

The Water Authority: Let the true per unit cost of water exceed the private cost by the amount γ: so the true per unit cost of water is $c + \gamma$. The parameter γ may represent the cost of delivering the water to farmers' gates, or the extraction externalities associated with pumping from a shared aquifer, or the scarcity cost of water, or any combination of these. The regulator seeks to induce farmers to use water to the point where its value of marginal productivity equals its true cost, i.e., she wants farmers to use water efficiently. If the regulator could observe water applications or knew each farmer's type, efficiency could be attained by charging farmers the per unit water fee γ for each unit of water use. In such ideal situations, each farmer would choose a level of output $Y^i(p, c + \gamma, \beta^i)$, that maximizes $pY^i - (c + \gamma)W(Y^i,\beta^i)$, i.e., choose a *first-best* output level satisfying

$$p - (c + \gamma)W_1(Y^i(p,c+\gamma, \beta^i),\beta^i) = 0,$$

and use the corresponding water level $W(Y^i(p, c+\gamma, \beta^i),\beta^i)$, $i = 1,2,\ldots,n$.

Charging for water use directly, however is not feasible when farmers' types and water applications are private information. In the situation considered here the regulator knows c and observes each farmer's output level, but is unable to observe any farmer's water applications and types. The regulator's prior beliefs concerning β^i are represented by the distribution function $F(\beta^i)$, with density $f(\beta^i) > 0$, $\beta^i \in [0,1]$. Thus, the β^i are independent and identically distributed according to $F(\cdot)$ and this distribution is common knowledge.

Lacking knowledge of water use, the regulator collects water fees based on observable output. Denote the fee schedule facing farmer i by $T^i(Y^i)$. Farmer i's profit is

$$pY^i - c\,W(Y^i, \beta^i) - T^i(Y^i), \quad i = 1,\ldots,n.$$

The regulator's problem is to determine the tax schedules $T^i(Y^i)$ that induce efficient water use.

3. The Pricing Mechanism

An optimal pricing mechanism (tax schedules) is constructed by using the following direct revelation mechanism[2] (Myerson, 1979, 1989): (i) To each farmer, the regulator announces (and commits to) the set of contracts $\left\{T^i(\tilde{\beta}^i), Y^i(\tilde{\beta}^i)\right\}_{\tilde{\beta}^i \in [0,1]}$, composed of a tax schedule $T^i(\tilde{\beta}^i)$ and an output schedule $Y^i(\tilde{\beta}^i)$, both of which depend on the type reported by farmer i. (ii) After observing the schedule, each farmer reports $\tilde{\beta}^i$ to the regulator. (iii) The regulator observes each $\tilde{\beta}^i$ and offers farmer i the contract $(T^i(\tilde{\beta}^i), Y^i(\tilde{\beta}^i))$, $i = 1,\ldots,n$, indicating that farmer i pays $T^i(\tilde{\beta}^i)$ to produce $Y^i(\tilde{\beta}^i)$ units of output. A direct revelation mechanism (DRM) is truthful if it is in the interest of each farmer to report his type truthfully when all other farmers report honestly. Under truthtelling, $\tilde{\beta}^i = \beta^i$ for all i.

Given truthtelling, the profit of a type-β^i farmer reporting $\tilde{\beta}^i$ is

$$\pi(\beta^i) = p\,Y^i(\beta^i) - cW(Y^i(\beta^i),\beta^i) - T^i(\beta^i), \tag{2}$$

Smith and Tsur show that truthfully revealing his type is farmer i's optimal response if and only if, for all $\tilde{\beta}^i \in [0,1]$:

$$\frac{d}{d\beta^i}\pi^i(\beta^i) = -cW_2(Y^i(\beta^i),\beta^i),\ i = 1,\ldots,n, \tag{3}$$

$$\frac{\partial}{\partial\tilde{\beta}^i}Y^i(\tilde{\beta}^i) \geq 0. \tag{4}$$

Equation (3) is the envelope condition for truthtelling and says that farmer profits are strictly increasing in farmer type. Equation (4), results from the second order condition for truthtelling and simply requires that the output schedule be nondecreasing in $\tilde{\beta}^i$. Since profits are increasing in β^i, farmers are ensured a nonnegative profit if

$$\pi^i(0) = r^i \geq 0, \tag{5}$$

where without loss of generality we set r^i, the minimum profit level, equal to zero.

The Optimal Truthful Revelation Mechanism

In principle, the set of truthful DRMs satisfying constraints (3), (4), and (5) may be quite large. Using (2) and letting $\alpha = c + \gamma/(1-\lambda)$, Smith and Tsur show that the regulator's problem[3] is:

$$\text{(P1)}\qquad \max_{\{Y^i,\ldots,Y^n\}}\left\{E_\beta \sum_{i=1}^{n}\left\{(1-\lambda)\left[p\,Y^i(\beta^i) - \alpha W(Y^i(\beta^i),\beta^i)\right] + \lambda\pi^i(\beta^i)\right\}\right\}$$

subject to (3), (4), and (5).

Here, $\lambda \geq 0$, is the transaction cost of implementing the tax scheme, and is the expected cost of each tax dollar raised ($\lambda = 0$ corresponds to zero transaction costs).[4] Define

$Z(\beta^i) = c\lambda[1 - F(\beta^i)] / (1-\lambda)f(\beta^i)$. The following assumption further simplifies (P1):

Assumption 1: (i) $W_{211} \geq 0$. (ii) $W_{122} \leq 0$ and (iii) $Z'(\beta^i) + \alpha \geq 0$.

Marginal water use is concave in type [assumption 1(ii)] and the inverse hazard rate does not decrease too fast [assumption 1(iii)]. Elsewhere we show that:

Proposition 1: Given assumptions 1, the optimal output schedule, $Y^{i*}(\beta^i)$, satisfies:

$$p - \frac{\lambda}{1-\lambda}\left(\frac{1 - F(\beta^i)}{f(\beta^i)}\right)cW_{21}(Y^{i*}(\beta^i),\beta^i) = \left(c + \frac{\gamma}{1-\lambda}\right)W_1(Y^{i*}(\beta^i),\beta^i). \tag{6}$$

and is nondecreasing.

The marginal benefit to the type-β^i farmer is equal to marginal total social cost. Here, the marginal benefit to a type-β^i farmer is composed of output price and an informational rent ($-Z\,W_{21}$). The latter term is the minimum amount a type-β^i farmer will take to reveal his type. If a type-β^i farmer is allowed to increase output by a small amount then his marginal profits increase by an amount $-cW_{21}$. Since $d\pi^i / d\beta^i = -cW_2$, integrating $-cW_2$ between zero and β^i gives the type-β^i farmer's profit. Hence, when marginal profit to the type-β^i farmer increases, so does the marginal profit of all other farmers with types in the interval $[\beta^i,1]$; and farmers will have such types with probability $1 - F(\beta^i)$. Also, the higher the value of λ, the higher the informational rent received by farmers. The marginal cost of water use is the product of the change in water use given a change in output (inverse of the marginal product of water) and $c + \gamma / (1-\lambda)$, the farmer's personal per unit cost of water plus the weighted per-unit cost of water delivery.

From expression(6), the absence or presence of transaction costs determines whether or not the regulator is indifferent to transfers (taxes), and hence, whether or not farmers can appropriate informational rents from the regulator. Also, transaction costs increase per-unit water delivery costs. When $\lambda = 0$, the tax schedule drops out of the social objective function, informational rents are zero and the per unit cost of water delivery is equal to γ. In this case output is chosen so that $p = (c+\gamma)W_1$, attaining a first-best allocation.

Transaction costs also influence the slope of the output function, equation (4). For example, ignoring equation (4), if $\lambda = 0$ then it can be shown that the slope of the output schedule satisfying (6) is:

$$\frac{dY^i}{d\beta^i}(\beta^i) = -\frac{W_{21}(Y^i(\beta^i),\beta^i)}{W_{11}(Y^i(\beta^i),\beta^i)} > 0.$$

In other words, with zero transaction costs the regulator can ignore both assumption 2 and equation (4). However, if λ is strictly greater than zero and assumption 2 is violated, then the regulator cannot ignore (4). We will refer to the output schedule satisfying (6) while ignoring equation (4) as the *unrestricted output schedule*. We do not discuss the technical details of how the optimal output schedule is chosen when assumption 2 is violated (these can be found in Guesnerie and Laffont [1984] or Fudenberg and Tirole [1991]).

When transaction costs are present, all but type-1 farmers earn informational rents, per-unit water-delivery costs increase, and first-best allocations are unattainable. In fact, for a given β^i, higher transaction costs imply greater informational rents and greater marginal total social costs: with both increasing at an increasing rate for $\lambda > 0$. With strictly positive transaction costs, optimal output levels are chosen so that marginal total social cost, $(c+\alpha)W_1$, are greater than price; hence, for each farmer-type, optimal (regulated) output levels are less than first-best levels.

The tax schedule is derived by integrating (3) between 0 and β^i and using (2) to get:

$$T^{i*}(\beta^i) = pY^{i*}(\beta^i) - cW(Y^{i*}(\beta^i),\beta^i) + \int_0^{\beta^i} cW_2(Y^{i*}(s),s)ds. \tag{7}$$

Smith and Tsur show that the optimal tax function is nondecreasing. The optimal truthful DRM, then, is a pair of nondecreasing tax and output schedules, $\{Y^{i*}(\beta^i), T^{i*}(\beta^i)\}$, satisfying equations (6) and (7) respectively.

The optimal nonlinear tax as a function of Y, denoted $\mathcal{T}^{i*}(Y)$, is obtained from

$$\mathcal{T}^{i*}(Y) \;=\; pY - cW(Y,h(Y)) + \int_{\underline{Y}}^{Y} cW_2(Y,h(Y))\,h'(Y)\,dY, \qquad Y > \underline{Y},$$

where $\underline{Y} = Y(0)$ and h is the inverse image of $Y^*(\beta^i)$.

4. Numerical Example

To illustrate the above procedure, consider the case of regulating one farmer whose water response function is given by $g(w, \beta) = (1+\beta)w^{0.5}$, where β (with the i superscript suppressed) is distributed uniformly on [0,1]. Assuming that $c = 1$, $p = 5$ and $\gamma = 0.5$, the water demand function is $W(Y, b) = 0.25*[Y/(1+b)]^2$ and the farmer's profit is; $5y - 0.25[Y/(1+\beta)]^2$. The analytic solutions for the first-best output schedule and the optimal output schedule under no regulation are presented in Table 1. Also, the unrestricted output schedules and the tax schedules for the case where $\lambda = 0$ and $\lambda = 0.2$ are presented in the same table.

	Output schedule	Tax schedule
Unregulated	$10\,(1+\beta)^2$	...
First-Best	$6.67\,(1+\beta)^2$	...
Regulated, $\lambda = 0$	$6.67\,(1+\beta)^2$	$22.22 + 11.11\,[2\beta + \beta^2]$
Regulated, $\lambda = 0.2$	$\dfrac{2.5(1+\beta)^2}{0.5+\beta}$	$-2.95-2.15\beta-5.5\beta^2+\dfrac{1.15}{0.51+\beta}-\dfrac{16(1+\beta)^4}{(0.9+1.7\beta)^2}+\dfrac{40(1+\beta)^3}{0.9+1.7\beta}-7.36\,\mathrm{Ln}(0.9+1.7\beta)$

Table 1

The water response function satisfies (1), but violates assumptions 1 and 2.i; implying that the unrestricted output schedule may not be nondecreasing. The unrestricted output schedule was chosen for values of λ in the interval [0,10]. Using *Mathematica*, numerical analysis of the properties of the unrestricted output schedule reveals that the unrestricted output schedule is strictly increasing whenever $\lambda \in [0, 0.3]$ or $\lambda > 1.5$. So, in this example, the regulator can ignore the monotonicity constraint only if transaction costs are between zero and 0.3 or are greater than 1.5.

Table 2 shows that with no transaction costs expected net social benefit under regulation is equal to the total expected net social benefit in a first-best world. The output schedule with no regulation, and the unrestricted output schedules under regulation are depicted in figure 1 (with λ equal to 0, 0.3, and 1.6). For each value of β, the slope of the unrestricted output schedule decreases as λ increases from zero to 0.34. This is shown more clearly in the surface of figure 2; where the output produced by the lowest farmer-type increases (the highest type farmer decreases) as λ increases.

	No Regulation	First-Best	Regulated				
			$\lambda = 0$	$\lambda = 0.1$	$\lambda = 0.3$	$\lambda = 1.6$	$\lambda = 1.8$
Total Expected Net Benefit	29.17	38.89	38.89	32.02	15.15	-95.38	-87.16

Table 2.

The numerical example also shows that given the class of mechanisms considered here, even when incentive schemes can be designed that separate farmers completely (each different farmer type is given a different contract), if λ is large enough, the cost of implementing the policy might outweigh the benefits of attaining second best efficiency. For example, table 2 shows that when $\lambda = 1.6$ the expected net benefit without regulation (29.17) is greater than that with regulation (-98.38). Obviously this particular outcome results from our particular choice of W and the chosen values of p, c, and γ. But, this suggests that when monitoring and implementation costs are high irrigation water should be priced on a fixed fee or a per hectare basis. On the other hand, if these costs are low, then one might expect to see output based tax schemes. Such schemes have been observed in Egypt and Thailand. In Egypt, part of the costs of large scale irrigation projects have been defrayed by taxes on wheat exports (Bowen and Young).

As with the unrestricted output schedule, the tax schedule's behavior varies with different values of λ. Figure 4 shows that the tax schedule is strictly increasing when λ is equal to zero, 0.1 or 10. For λ between 1.5 and about 2.5 the tax schedules first increase at an increasing rate then decrease (see the tax schedule for $\lambda = 1.8$ in figure 4). In these cases, apparently, given that the output schedule is strictly increasing, output price eventually falls below the farmer's marginal cost, and hence the tax rate must fall to induce the farmer to produce in such a manner. For λ greater than 2.6, the tax schedules are increasing convex functions.

5. Discussion and Conclusion

The presence of externalities, the intertemporal nature, a small number of participants and various types of uncertainty, all tend to limit the scope of market mechanisms in allocating water resources. Consequently, some form of public intervention and regulation is often needed. Regulation may come in the form of setting quantity quotas, setting prices or a combination of these. In the pervasive case where individual water use are unobserved (water is unmetered), neither of these regulation approaches is directly applicable. Often, output or some inputs are easier to observe because they are purchased in the marketplace. If production technologies were perfectly known, the observed output could be used to evaluate individual water use. Information on individual production technologies, however, is private and collecting it is costly (at least as costly as collecting information on water use).

We offered above a pricing mechanism for unmetered water when individual production technologies are private information. The procedure makes use of observed output and implicitly elicits information on individual production technologies by means of a direct revelation mechanism. Implementation of the pricing mechanism requires information on individual outputs, which is often more accessible than information on production technologies or water applications. The pricing procedure entails imposing a tax on output. If implementing such a tax is free of transaction costs, our scheme attains a first best allocation (i.e., the optimal allocation when individual water uses are observed). With transaction costs, a second-best allocation is achieved. A numerical example corroborates the properties of the pricing mechanism. It also reveals that beyond a certain level of transaction costs, the economy is better off without regulation.

Footnotes

1. See Smith and Tsur.

2. Smith and Tsur begin by considering a more general (random) direct revelation mechanism, but eventually impose restrictions on $W(\cdot\cdot)$ that guarantee that the optimal incentive scheme offered to farmer i will be a function of farmer i's type only.

3. The expression V is equal to the sum of the farmers' net profit under regulation,

$\sum_{i=1}^{n} py^i - c\,W(y^i, \beta^i) - t^i$, plus the regulators net benefit, $\sum_{i=1}^{n} t^i - \lambda t^i - \gamma\, W(y^i, \beta^i)$, where λt^i is the transaction cost per tax dollar raised. In this case then, the social cost of a dollar of tax is $(1 + \lambda)$. Then, the tax function $t^i(\beta^i)$ is eliminated using expression (4).

4. Transaction costs include costs associated with administration, monitoring and enforcing activities. For example, we assume each individual farmer's output is observable, however, we do not necessarily assume that it is observable without cost. If, for instance, the water is used to produce a commodity that has value only in export markets, a marketing board exports the commodity, and farmers must deliver the commodity to the marketing board to receive compensation (and it is very costly for farmers to circumvent the marketing board); then transaction costs might be viewed as negligible. However, if the regulator must visit each farmer periodically during the growing season, doing so might become costly.

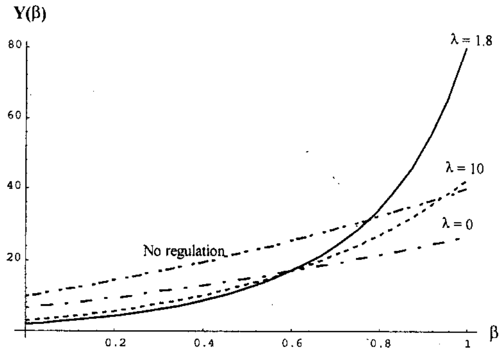

Figure 1. Output schedules under regulation and no regulation (First best: $\lambda=0$)

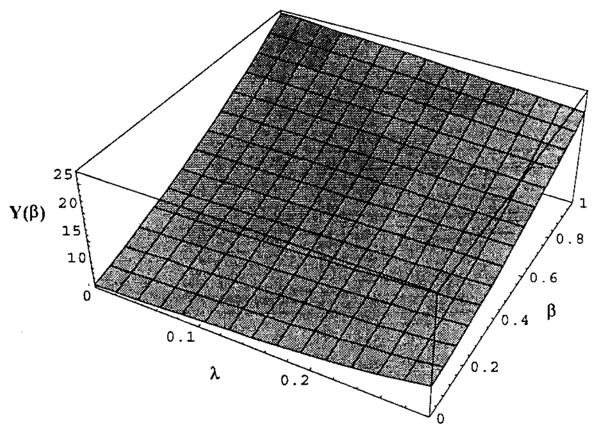

Figure 2. Unrestricted output schedule for $\lambda \in [0, 0.3]$

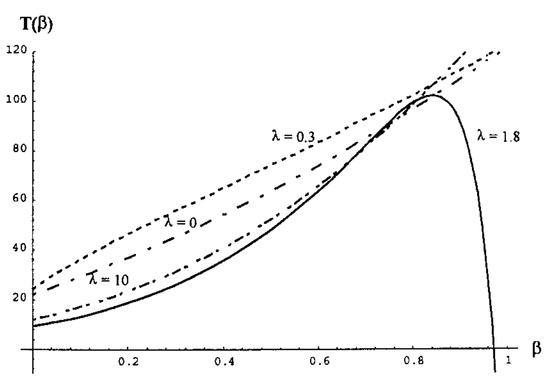

Figure 4. Optimal tax schedules (First best: λ = 0)

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1. To verify, differentiate both sides of $W(g(w, b^i), b^i) = w$ with respect to w and b to obtain respectively,

$$\text{(i) } W_1 g_1 = 1; \qquad \text{(ii) } W_1 g_2 + W_2 = 0.$$

By assumption $g_1 > 0$, and hence by (i) $W_1 > 0$. Also, by assumption $g_2 > 0$, and given $W_1 > 0$ and (ii) it follows that $W_2 < 0$. Differentiating (i) with respect to w gives $W_{11}g + W_1 g_{11} = 0$. With $g_{11} < 0$ it follows that $W_{11} > 0$. Finally, differentiating (i) with respect to b gives $[W_{11}g_2 + W_{12}]g_1 + W_1 g_{12} = 0$, from which one concludes $W_{12} < 0$.

2. Smith and Tsur begin by considering a more general (random) direct revelation mechanism, but eventually impose restrictions on $W(\cdot\cdot)$ that guarantee that the optimal incentive scheme offered to farmer i will be a function of farmer i's type only.

3. The expression V is equal to the sum of the farmers' net profit under regulation, $\sum_{i=1}^{n} py^i - c\,W(y^i,\beta^i) - t^i$, plus the regulators net benefit, $\sum_{i=1}^{n} t^i - \lambda t^i - \gamma\, W(y^i,\beta^i)$, where λt^i is the transaction cost per tax dollar raised. In this case then, the social cost of a dollar of tax is $(1 + \lambda)$. Then, the tax function $t^i(\beta^i)$ is eliminated using expression (4).

4. Transaction costs include the costs associated with administration, monitoring and enforcing activities. For example, although we assume each individual farmer's output is observable, we do not necessarily assume that it is observable without cost. If (i) the water is used to produce a commodity that has value only in export markets, (ii) a marketing board exports the commodity, (iii) farmers must

deliver the commodity to the marketing board to receive compensation, (iv) and it is very costly for farmers to circumvent the marketing board; then transaction costs might be viewed as very small or zero. However, if the water authority must visit each farmer periodically during the growing season, doing so might become costly.