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Institutions for Managing Ground and Surface Water and the Theory of the Second-Best

By

Karl Jandoc
Richard Howitt
James Roumasset
Christopher Wada

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Karl Jandoc†, Richard Howitt‡, James Roumasset§, and Christopher A. Wada¶

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Abstract

We review the theory of optimal conjunctive-use management absent transaction costs as a point of departure for a second-best theory of management. We first explore the problem of optimal pricing of surface water when groundwater remains unregulated. We then move to consideration of institutional mechanisms for managing groundwater. The last section discusses the transaction cost difficulties with water markets and how these can be mitigated with remote sensing technology, much as barbed wire facilitated private property in the American West.

Keywords: Groundwater management, Second-best policy, Conjunctive use, Water institutions, Institutional change.

JEL Classification Q25 · D23 · H21 · P14

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†Department of Economics, University of Hawai'i at Mānoa, Honolulu, Hawai'i, USA. Email: kljandoc@hawaii.edu

‡Department of Agricultural and Resource Economics, University of California at Davis, Davis, California, USA. Email: howitt@primal.ucdavis.edu

§Department of Economics, University of Hawai'i at Mānoa, and University of Hawai'i Economic Research Organization, Honolulu, Hawai'i, USA. Email: jimr@hawaii.edu

¶University of Hawai'i Economic Research Organization, Honolulu, Hawai'i, USA. Email: cawada@hawaii.edu

1 Introduction

This paper derives principles of water pricing using a simple model of conjunctive use. We begin with a review of first-best principles for the joint management of ground and surface water, i.e. in abstraction from transaction costs. Inasmuch as information and enforcement costs are pervasive in water management, however, how can we extend the conventional water management theory to account for transaction costs?

In what follows, we recognize two types of second-best analysis. The first involves adding a constraint to an otherwise first-best problem. For example, optimal taxation is concerned with the optimal markup of the tax-inclusive price above marginal cost in the presence of a minimum constraint on tax revenue and, because of a missing market, the inability to tax labor. In the conjunctive-use context, this corresponds to the problem of how to price irrigation water when groundwater use is unregulated.

The second type of 2nd-best analysis involves the comparative analysis of alternative institutions regarding their ability to simultaneously enhance the benefits of economic cooperation and economize on transaction costs (Roumasset [17], Williamson [21]). We consider the case of optimal governance of groundwater.

2 Second-best pricing of surface water with unregulated groundwater

There is an abundant literature on the importance of water pricing to implement demand-side conservation. This has led to the spread of markets for irrigation water in several parts of the U.S., Australia, Israel, and several developing countries (Tsur et al. [20]). While most of the literature on the economics of surface and groundwater management is at the first-best level of analysis, groundwater is often left unpriced due to administrative costs of regulatory arrangements. Pricing surface water at its full opportunity cost in such situations may induce some farmers to switch to groundwater thereby exacerbating the open access problem. There remains an "unpaid factor" externality because farmers are not paying for the marginal user cost of groundwater. Once this externality is taken into account, how is the optimal surface-water price affected, given that the costs of directly pricing or regulating are excessive. Just as taxing complements of untaxed leisure higher than other goods is second-best (Corlett and Hague [7]), one suspects that pricing water lower than its first-best level will partially ameliorate that externality. It is even conceivable that creating a market for surface water, without groundwater regulation, could decrease welfare relative to leaving surface water unpriced. This section extends the Chakravorty-Umetsu [5] model of the 1st-best boundary between groundwater and surface water to the case of second-best.

2.1 Model setup and optimal conjunctive use in the absence of transaction costs

We begin with a simplified version of the model in Chakravorty and Umetsu [5]. Farms are located along a continuum with the headworks located upstream. These farms differ only by their distance from the source, which we denote by x, and are similar in all other respects. We assume that the command area is a fixed distance $\bar{x}$. Water sent from the headworks to a farm located at distance x is denoted by $Q(x)$. Some of the water that flows through the canal is lost in conveyance because of seepage and percolation. Therefore the amount of *received water* at distance x is given by $q(x) = Q(x)h(x)$ where $h(x)$ is the conveyance efficiency ($0 < h(x) < 1$) which is a decreasing function of distance, that is, $h'(x) < 0$. The constant marginal cost of *sent* water is denoted by c_s, and hence the marginal cost of received water at distance x is given by $\frac{c_s}{h(x)}$. Apart from surface water, farms also have access to groundwater. The use of groundwater at distance x is given by $g(x)$. The marginal extraction cost of groundwater, c_g, as well as the marginal user cost of groundwater, λ, are assumed to be constant.[1] The benefit of water use is given by the function, $B(\omega(x)) = \int_0^{\omega(x)} p(\gamma)d\gamma$, where $\omega(x) = q(x) + g(x)$ and $p(\omega)$ is the inverse demand function $\left(\frac{dp}{d\omega} < 0\right)$. The benefit function is assumed to be concave. The water authority wishes to maximize the net benefit of water use by choosing the boundary of surface water use. This is given by the equation:

$$\max_{q(x),g(x)} V = \int_0^{\bar{x}} \left(B(\omega(x)) - \frac{q(x)c_s}{h(x)} - g(x)(c_g + \lambda) \right) d\lambda \tag{1}$$

As in Chakravorty and Umetsu [5] and chapter XX of this Handbook, farmers closer to the surface water headworks have a comparative advantage in using surface water. That is, there is a unique boundary x^* at which farmers located before x^* exclusively use surface water and those farther away exclusively use groundwater. Hence, we can write 1 by decomposing it into farms using surface water exclusively and those who use groundwater exclusively:

$$\max_{x^*} V = \int_0^{x^*} \left(B(\omega(\theta)) - c_s \frac{q(\theta)}{h(\theta)} \right) d\theta + \int_{x^*}^{\bar{x}} \left(B(\omega(\psi)) - g(\psi)(c_g + \lambda) \right) d\psi \tag{2}$$

Note that $\omega(x) = q(x)$ for $x \leq x^*$ and $\omega(x) = g(x)$ for $x > x^*$.

As in Coasean economics (e.g. Coase [6]), it is instructive to abstract from transaction costs as a point of departure. In this case, the marginal benefit

[1] In a dynamic setting, the marginal user cost would change over time in response to changes in various factors that affect water scarcity such as depth to groundwater and current precipitation.

(inverse demand function) of all those who exclusively use surface water equals the full marginal cost of surface water at distance x, that is, $B'(q(x)) = \frac{c_s}{h(x)}$. Also, the marginal benefit of those who exclusively use groundwater equals the marginal extraction cost plus the marginal user cost, that is, $B'(g) = c_g + \lambda$. The unique boundary is found by the equality of marginal benefits at that point. This means that at the boundary:

$$\frac{c_s}{h(x^*)} = c_g + \lambda \tag{3}$$

The first best solution might be implemented, for example, by setting the wholesale price of water released from the headworks at c_s and pricing groundwater at $c_g + \lambda$. Alternatively, the same solution could be implemented by quantity controls.

2.2 Surface water markets with open access in groundwater

As motivation for the case of optimal groundwater pricing in the face of unregulated groundwater, consider the equilibrium allocation under a market for surface water but unregulated groundwater. In this case, the first-best solution cannot be implemented. Farmers will not internalize the full marginal cost of groundwater, but rather, will use groundwater up to the point where its marginal benefit equals the (constant) marginal extraction cost, that is, groundwater is extracted up to $\tilde{g}$ where $B'(\tilde{g}) = c_g$. The boundary $\tilde{x}$ in this case is determined by the equality of marginal benefits of *received* water and groundwater at that point. Since the marginal benefit of surface water at $\tilde{x}$ is given by the equality $B'(q(\tilde{x})) = \frac{c_s}{h(\tilde{x})}$, it follows that the boundary $\tilde{x}$ is determined by the equation

$$c_g = \frac{c_s}{h(\tilde{x})} \quad (4)$$

This equation says that at $\tilde{x}$, the marginal extraction cost of groundwater and the marginal cost of received water at that distance are equal. Clearly, since in open access farmers draw more groundwater than in the first best solution (at open access marginal user cost is ignored), the boundary $\tilde{x}$ should be closer to the surface water source than the first best boundary, x^*. But since the marginal social cost of groundwater, $c_g + \lambda$, is greater than marginal benefits under open access, groundwater is overused.

2.3 Second-best pricing of surface water in the absence of groundwater regulation

The problem is now to choose the price of surface water in order to maximize net benefits, subject to the constraint that groundwater is unregulated. The water authority in this situation can induce people to economize on groundwater by subsidizing the price of surface water.[2] In this second-best scenario, the water authority maximizes 1 subject to the constraint that at the boundary the marginal benefit of surface water use equals the marginal extraction cost. With the subsidy, the marginal benefit of surface water use is equal to the marginal cost of surface water minus the subsidy, that is:

$$B'\left(q(x)\right) = \frac{c_s - s}{h(x)} \quad (5)$$

where s is the per-unit subsidy of surface water. Therefore, at the second-best boundary x^{**}, we have that

[2]Later in the chapter, we discuss the case of Orange County which uses this subsidization mechanism to maintain their coastal ground water mound (stock).

$$\frac{c_s - s}{h(x^{**})} = c_g \tag{6}$$

Thus, the water authority wishes to find the boundary x^{**} at which net benefits are maximized subject to the constraint that at the boundary the marginal benefit of surface water use equals the marginal extraction cost of groundwater, that is, the problem is:

$$\max_{x^{**}} V = \int_0^{x^{**}} \left(B(\omega(\theta)) - c_s \frac{q(\theta)}{h(\theta)} \right) d\theta + \int_{x^{**}}^{\bar{x}} \left(B(\omega(\psi)) - g(\psi)(c_g + \lambda) \right) d\psi \tag{7}$$

subject to equation 6.

However, raising the revenue required for the subsidy to surface water users creates "tax friction," due to the distorted incentives imposed by the taxes needed to finance the subsidy (Ballard, Shoven and Whalley [3]). Hence, we modify equation 7 to include the excess burden of tax friction as follows:

$$\max_{x^{**}} V = \int_0^{x^{**}} \left(B(\omega(\theta)) - c_s \frac{q(\theta)}{h(\theta)} - \alpha s \frac{q(\theta)}{h(\theta)} \right) d\theta + \int_{x^{**}}^{\bar{x}} \left(B(\omega(\psi)) - g(\psi)(c_g + \lambda) \right) d\psi \tag{8}$$

subject to equation 6. Here α is the estimated tax friction and $S = \int_0^{x^{**}} s \frac{q(\theta)}{h(\theta)} d\theta$ is the total subsidy given to surface water users.

2.4 Numerical example

We illustrate the results with a numerical example. Suppose that $c_s = 1$, $c_g = 2$ and $\lambda = 4$. Assume that the benefit function for water use is $B(\omega(x)) = \omega(x)\left(10 - \frac{\omega(x)}{2}\right)$. Let the conveyance efficiency function be $h(x) = e^{-.02x}$ for each x kilometers. Let the command area be $\bar{x} = 100$ kilometers. In the first best scenario, the boundary x^* is determined as the solution to equation 3.

$\frac{c_s}{h(x^*)} = c_g + \lambda \Rightarrow h(x^*) = \frac{1}{6} \Rightarrow x^* = \frac{ln(6)}{.02} \Rightarrow x^* \approx 89.6$km.

In the case of open access, the boundary $\tilde{x}$ is likewise computed as the solution to equation 4

$\frac{c_s}{h(\tilde{x})} = c_g \Rightarrow h(\tilde{x}) = \frac{1}{2} \Rightarrow x^* = \frac{ln(2)}{.02} \Rightarrow x^* \approx 34.7$km.

We see in this example that the open access boundary is closer to the source than the first best boundary, which implies that more farmers use the groundwater resource under open access. Intuitively, since farmers do not have to pay the full opportunity cost of groundwater under open access, more farmers use groundwater than the fully priced surface water.

In computing the second best boundary x^{**} we do the following steps: First, we guess a value of the second-best boundary, say 50 km, and we compute the subsidy s using equation 6. Second, we use this subsidy and find an expression for $q(x)$ using the condition that the marginal benefit of surface water should be equal to the marginal extraction cost (minus the subsidy). Third, we use the expression of $q(x)$ and plug this into the net benefit function in equation 7 or equation 8, along with the corresponding amounts of groundwater obtained by the solution to $B'(\tilde{g}) = c_g$, to compute the corresponding net benefit. We do this step for the case where we do not assume a tax friction and for the case where tax friction is estimated to be 30% of the total subsidy. Finally, we iterate this process by choosing another boundary and compute the corresponding net benefit. The boundary x^{**} is at the level where net benefits are maximized.

Case 1 in Table 1 illustrates the boundaries in this system, the optimal quantities of sent water and groundwater extraction as well as the total subsidy and subsidy per unit of sent water in the scenario with no tax friction. Case 2 illustrates the case where tax friction is 30% of the total subsidy.

For the tax friction case, the subsidy of surface water ($0.54) is slightly

Table 1: Open access, first best and second best with and without tax friction

	Case 1			Case 2		
	Open access	First best	Second best	Open access	First best	Second best
Total quantity of:						
Sent water, Q	425	1,625	2,022	425	1,625	1,488
Groundwater extraction, g	523	42	112	523	42	208
Net welfare (in 10^6 US$) from:						
Surface water	1,270.37	2,416.90	2,229.61	1,270.37	2,416.90	1,921.18
Groundwater	0	83.29	0	0	83.29	0
Total	1,270.37	2,500.19	2,229.61	1,270.37	2,500.19	1,921.18
Boundary (kms)	34.7	89.6	86	34.7	89.6	74
Total subsidy ($)			1,298			811
Subsidy per unit Q ($)			0.641			0.541

Note: In Case 1, we disregard tax friction. In Case 2, tax friction is equal to 30% of total subsidy.

more than half of the wholesale price and cuts the welfare loss of open access by slightly more than half as well (from $2500 million - $1270 million to $2500 million- $1921 million). The relatively large subsidy of surface water moves the second-best boundary (74 kms.) most of the way from the open access boundary of 34.7 km towards the first-best boundary of 89.6 kms. In this particular example, each unregulated groundwater farmer gains rents that are exactly offset by the excess burden associated with ignoring the MUC. By subsidizing surface water, more farmers end up in the surface water category and garner rents in excess of even the full cost.

Now suppose that groundwater is depleted over time, prior to reaching a steady state. In this case, both the marginal extraction cost and the marginal user cost of groundwater extraction increase. Suppose the new marginal extraction costs and marginal user costs increase to $c_g = 2.25$ and $\lambda = 4.5$ (from 2 and 4 respectively). As seen in Case 3 in Table 2, this increase in the scarcity value of groundwater moves the boundaries for the open access, first-best and second-best cases to 40.5, 95.5 and 79 km, respectively. The subsidy of surface water slightly decreases to $0.53. There is a significant loss in welfare from groundwater extraction for all the cases, but is ameliorated by the welfare gain of farmers switching to surface water.

Table 2: Open access, first best and second best when groundwater is scarce

	Case 3		
	Open access	First best	Second best
Total quantity of:			
Sent water, Q	523	1,761	1,666
Groundwater extraction, g	461	15	163
Net welfare (in 10^6 US$) from:			
Surface water	1,453.11	2,455.89	1,955.26
Groundwater	-287.97	23.88	-101.72
Total	1,165.14	2,479.77	1,853.54
Boundary (kms)	40.5	95.5	79
Total subsidy ($)			894
Subsidy per unit Q ($)			0.536

Note: In Case 3, we include the same value of tax friction (30%) but let marginal extraction cost and marginal user cost of groundwater rise to 2.25 and 4.5, respectively.

3 The Evolution of Optimal Groundwater Governance

In this section, we portray a different level of second-best analysis by explicit treatment of transaction costs. For this purpose, we focus only on optimal groundwater extraction.

In many regions around the world, groundwater is pumped from private wells for irrigation of crops. When a common pool resource such as groundwater faces overuse by multiple users with unrestricted extraction rights, additional governance may be warranted if the gains from governance exceed the costs (Demsetz [8]; Ostrom [16]). As discussed in the previous section, the optimal first best solution may be unattainable if one of the resources such as groundwater cannot be directly managed. However, even if no such restriction is in place, the first best solution may remain out of reach when enforcement and information costs are considered. Which of several institutions (e.g. privatization, centralized ownership, user associations) maximizes the net present value of the groundwater resource depends on the benefits generated from each option net of the governance costs involved in establishing and maintaining the candidate institution. For example, if the demand for water is small relative to the size of the aquifer, the gains from management are likely to be small, and open access might be preferred initially. As demand grows over time and water becomes scarcer, however, a common property arrangement (e.g., a user association) or a water market may become efficient.

Augmenting the standard groundwater optimization problem to allow for governance costs is fairly straightforward. Let the head level (h_t), which is the vertical distance between mean sea level and the top of the groundwater aquifer, be an index for the volume of stored freshwater. The groundwater stock increases with exogenous natural recharge (R) and decreases when water discharges from the aquifer to adjacent water bodies (d) or is pumped for irrigation (q_t), as described by the following equation of motion:

$$\dot{h} = R - d(h_t) - q_t \tag{9}$$

Pumped groundwater, which is an input to the production of crops, generates marginal benefit equal to P. The marginal pumping cost (c) is a function of the head level because more energy is required to lift groundwater a longer distance when the head is lower. Given q_t, the net benefit of resource use for society at time t is given by consumer surplus net of extraction costs:

$$NB_t = \int_0^{q_t} P(x)dx - c(h_t)q_t \tag{10}$$

Without governance, harvest will continue to the point where rent diminishes to zero. The associated open access harvest q_{oa} satisfies $P(q_{oa}(h)) = c(h)$. Note that the open access harvest at time t depends on the stock level in that period. Governance, which limits harvest to a level below q_{oa}, is costly. Governance costs may be incurred once or may be recurrent, but we begin by focusing on variable (recurring) costs of governance. Once the institution is established, the variable cost at each time t depends on the difference between open-access harvest and actual harvest:

$$G(q_t; q_{oa}) = g(q_{oa}(h_t) - q_t) \tag{11}$$

The plannerÕs problem is to choose extraction to maximize the present value of net benefits from resource use (Eq. 10) less governance costs (Eq. 11) subject to the aquiferÕs equation of motion (Eq. 9), i.e.

$$\max_{q_t} \int_0^{\infty} e^{-rt} \left[\int_0^{q_t} P(x)dx - c(h_t)q_t - g(q_{oa}(h_t) - q_t) \right] dt \tag{12}$$

subject to $\dot{h} = R - d(h_t) - q_t$ and $0 \leq q_t \leq q_{oa}(h_t)$ for all t.

To simplify the analysis, we further assume that the price (marginal benefit) of the resource is constant and the initial resource stock is above its steady state level. One can show that if the optimal solution involves positive governance (i) the groundwater stock decreases monotonically to its steady state level (ii) the shadow price of groundwater increases monotonically to its steady state level, and (iii) the steady state head level is lower than the first best level that would prevail if $g = 0$ (Roumasset and Tarui [18]). Figure 1 illustrates hypothetical dynamic paths of the full marginal net benefit (FMB) and shadow price (λ) of a groundwater aquifer in transition to governance.

The FMB of extraction is defined by $P - c(h_t) + g$, and the shadow price (λ) is the costate variable associated with the resource stock under the optimal solution. The non-instantaneous convergence of the FMB and λ appears to contradict the tendency to associate scarcity with net price or marginal user cost, the justification being that they are all equal along the optimal path in the standard management problem (without governance). However, this puzzle is resolved by examining one of the necessary conditions for the maximization

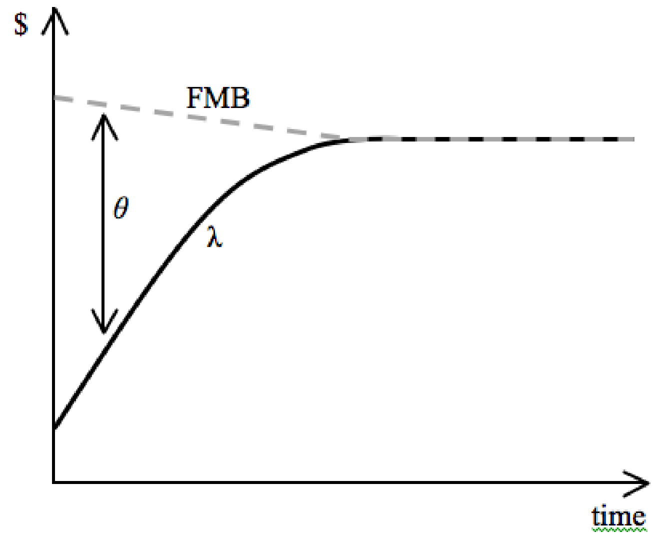

Figure 1: Full marginal benefit and shadow price under transition to governance

problem (Eq. 12):

$$P - c(h_t) + g = \lambda_t + \theta_t \tag{13}$$

where θ is the Lagrangian multiplier associated with the governance constraint. When g and θ are equal to zero in every period, the condition can be described as net price = MUC. When transition to governance is optimal, however, the FMB may be declining over time while the shadow price (the true scarcity value) is rising, and the difference between the two values is the shadow value of the binding governance constraint. Once the constraint is no longer binding, i.e. the optimal extraction quantity is less than open access, FMB and λ converge.

The speed of transition depends on the scarcity of the resource, the net price, and the cost of governance. As governance costs decrease due to advances in technology, e.g. improved satellite monitoring capabilities, we are able to move closer to the solution where the full marginal benefit is equal to the full marginal cost of groundwater.

4 From open access to common property to markets

In an open access regime where groundwater extraction is unregulated, farmers pump water until their rent from doing so is exhausted. In many countries there have been several forms of groundwater management that are designed to curb over-extraction of the resource. Examples of common property institutions are community-managed systems such as water users associations. A case study from Minquin County in China (Aarnoudse, et al [1]) revealed that water users associations have been instrumental in reducing excessive groundwater extraction. Such common property institutions rely on specific systems of reward and punishment, often including community monitoring. Market institutions, on the other hand, rely on price or quantity mechanisms to allocate water and utilize public enforcement mechanisms. In Hawai‘i, for example, the Board of Water Supply chooses the price per unit of groundwater extracted, consumers determine use, and the BWS extracts accordingly. Similarly in West Bengal, volumetric pricing is implemented by metering tubewell extraction (Mukherji [15]). One could imagine cases where the management authority sets quantities extracted and allows trading such that the market determines price. Due to conveyance costs, however, distribution charges would have to be added to the market-established wholesale price.

Figure 2 presents a heuristic illustration of how institutions of groundwater management could efficiently evolve from open access to common property to water markets. The downward sloping lines are the net marginal benefits of conservation, i.e. the marginal extraction cost plus the marginal user cost saved from not using the last unit minus the forgone marginal benefit of that unit, for three periods (0, 1, and 2). The upward sloping lines are the marginal costs of governance, i.e. the monitoring and enforcement costs as a function of conservation value, defined as the amount actual extraction is reduced from its open access level times the MUC. That is, the greater is the value of the resource (in terms of its shadow price), and the more pumping is restricted away from its open access level will, in turn, require higher governance costs. We also assume that the marginal governance cost schedule for water markets, G_{WM}, has a lower intercept and slope than that of common property, but that these advantages come only at the higher fixed cost of setting up markets as opposed to that water user associations, G_{CP}.

Beginning at time zero, note that water markets have the highest net gains before consideration of fixed costs. But assuming that these net gains are less than the requisite fixed costs, the optimal governance is at zero, i.e. open access is 2nd-best optimal (point A). At time 1, the optimal institution is at point B' (common property) if and only if the net gains from common property (triangle IB'G minus G_{CP}) is positive and larger than the net gains from water markets (triangle IB"F minus G_{WM}). At time 2, the optimal institution is at point D" (regulation) if and only if the net gains from regulation (triangle JD"F minus G_{WM}) is positive and is larger than the net gains from common property (triangle JD'G minus G_{CP}). Intuitively, when the resource is sufficiently abundant, open access may be optimal. When the resource is sufficiently scarce in the sense of high marginal opportunity cost of extraction, water markets may be warranted. In the intermediate range, common property institutions (e.g. water user associations or informal customs limiting extraction) may (or may not be) efficient. This exercise in comparative institutional analysis illustrates that one cannot rank the efficiency of institutions apart from their circumstances.

In particular, where groundwater is still plentiful, it may be prudent to delay restrictions, regulations, and market institutions. Nor should planners assume that one institution will always be appropriate.

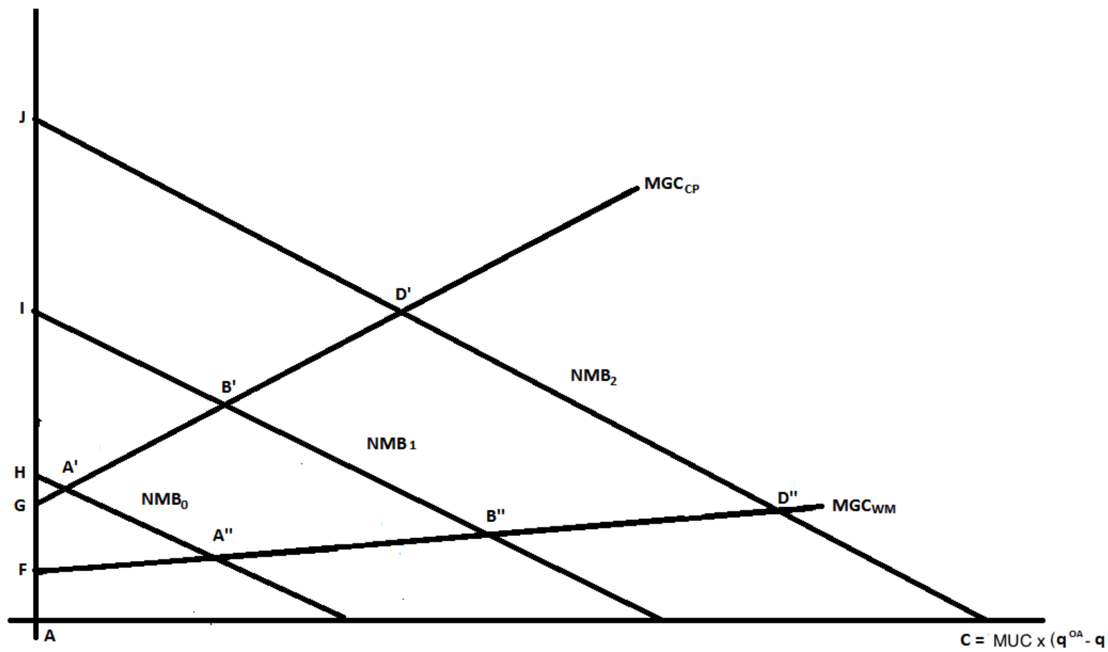

Figure 2: Evolution of groundwater governance (OA to CP to WM)

5 Satellite imaging to reduce measurement costs: the barbed wire of irrigation

5.1 The Fixed Costs of Water Market Institution

In the previous section, the optimal timing of the establishment of water management institutions was based on the evolution of benefits and costs of those institutions. In the analysis, the variable costs were defined as being continuous and well-behaved. The optimal timing of the switch from one institution to another is said to maximize net benefits, inclusive of institutional governance costs as depicted by equation 12. However, this equation abstracts from the fixed costs of starting, stopping, or switching institutions.

But as anticipated by the discussion of Figure 2, the question remains as to how do we determine when it is worth committing the fixed costs of establishing water market institutions? This section will address this question which is fraught with difficulties of non-convexity of establishment costs, uncertainties of the net benefits of the institution and its cost of operation, and the irreversible nature that seems to dog most institutional shifts. This section has two veins, first, we argue that the question of discrete changes in property rights should be analyzed using capital asset pricing theory pioneered by Dixit and Pindyck [9], which leads to the conclusion that there is a fixed total cost for the establishment of new institutions which needs to be compensated by additional benefits from its establishment over and above the expected returns. The second part of this section concentrates on some operational concepts of institutions with low transaction costs that may be able to compensate for the little costs expected in institutional establishment.

5.2 Institutional Innovation as a Discrete Capital Investment

Shifts in the nature of property rights for natural resources invariably involve a discrete switch point as illustrated by figure 2 shown in the previous section, and a significant investment in the lump sum of establishing the institutional monitoring system and enforcement. Clearly this fixed cost of institutional establishment will impede optimal solutions that consider only marginal costs.

In the classic paper on brand registration in the establishment of cattle property rights in the American West between 1850 in 1900, Anderson and

Hill [2] show that individuals and institutions increased time and resources devoted to the definition and enforcement of rights as the benefits increased and the costs (e.g. fencing with barbed wire) decreased. For example, cattle brands fluctuated with the prosperity of the industry which was significantly changed by the blizzards of the 1870s. The registration of brands in the local courthouses may have been quite comprehensive, but the enforcement of these brands by the regional Sheriff was very variable as demonstrated by many Western movies.

When applied to the question of when comprehensive institutions can be justified for water markets and groundwater management, the standard continuous marginal analysis breaks down under the pressure of the discrete non-convexity of establishment costs, uncertainties about the net benefits to overlying groundwater pumpers, and the costs of committing to a fixed institutional structure that has high costs of reversibility. The situation in several states in the Western US is the surface water rights are allocated based on prior appropriation which was formally recognizing 1855 in California in the case of Irving versus Phillips. The concept of reasonable use was first clarified in terms of groundwater and surface rights in 1903 in the case of Katz versus Wilkinshaw. Reasonable use was finally required for all water uses in California by a modification of the Constitution in 1928. A further modification occurred in the interpretation of reasonable use by a challenge 1967 in the case of Joslin versus Marin Municipal Water District (Gray [10]). In this case the property rights had to define between types of reasonable use and not merely rely on the concept of "first in time first in right" which had been the guiding principle up until that point. In the Joslin case the court had to distinguish between different types of values of use, essentially choosing between municipal uses of water from a diversion dam, versus the value of water washing gravel onto adjoining property from whence it was sold.

While these developments in the establishment of surface water rights and reasonable use were evolving, the situation with California and groundwater in other western states such as Texas remained with the laissez-faire concept of correlative property rights in which the overlying pumper has no restrictions on public unless injury can be proved by an adjoining groundwater pumper. In several Western states, for example California and Texas, there is a natural inclination by groundwater users against the establishment of fixed property rights. Users there strongly resist efforts to measure and monitor groundwater use, which is a prerequisite for operational groundwater management. In California, a recent multibillion-dollar water bill was held up in the state legislature until the provision for mandatory measurement of groundwater pumping measurement was removed and, as of this writing, California is still the only major Western irrigating state to still have no statewide groundwater management legislation enacted.

These ill-defined property rights for groundwater in the Western US is hardly surprising given uncertainty about how groundwater moved through the aquifers, its source of recharge, and the ability to accurately measure pumping extraction. An additional factor that makes the prospect of spending financial and political capital on establishing groundwater management less attractive is the relatively low cost of extracting groundwater in most Western states. Until recently, the relative abundance of groundwater in most areas makes the default position of remaining with undefined correlative rights one that was probably socially optimal.

The problem of establishing groundwater rights that enable more precise management can be characterized as a stochastic dynamic problem with discrete lump sum costs of institutional establishment in both fiscal and political terms. The economic benefits of managed groundwater can be summarized as resulting from excessive overdrafting of the aquifer and resulting increases in pumping cost to the overlying users. A second and possibly more valuable source of benefit has been characterized by Tsur and Graham-Tomasi [19] as the buffer stock value. This buffer stock value can be thought of as resulting from a difference in groundwater extraction capacity among different pumpers. Usually this is due to differences in well size and capacity, and in particular, the depth at which the screens on the wells are set to draw from different strata in the aquifer. Analysis of well log data shows that the depth of the top of well screens in California's central valley distributed is normally with a significant set of outlying wells having screens at higher levels. These small shallow wells are usually associated with small farms but these often grow very valuable crops. It follows that a given reduction in groundwater depth during drought years will have a differential impact on different groundwater pumpers. However, a small farmer is unlikely to have a portfolio of wells of different depths, and thus the social impact of groundwater is closer to a switching function rather than a continuous function in terms the damage for any one business, or group of businesses by size. In this case the benefit function from stabilization groundwater depth during dry years is stochastic event with a discontinuous cost function.

During the 1991 California drought the buffer value of groundwater in California, in particular in Butte County, was brought into sharp contrast by a lawsuit brought by a group of small farmers in the area termed the Cherokee Strip. The Cherokee Strip region is situated on a bench area on the edge of the Sacramento Valley which was significantly higher than the farms with more alluvial soil on the valley floor. As the drought progressed, an increasing number of small farm wells went dry in the Cherokee area and the Cherokee farmers petitioned to prevent farmers further down the hydraulic gradient on the valley floor from pumping their wells to the detriment of the Cherokee Strip groundwater depth. While the evidence for the hydraulic linkages between the groundwater in the two areas was disputed by the California Department of Water Resources, and was not found to be conclusive in the court hearings, the case had a significant effect on water markets and exports, and it spawned many locally enacted county ordinances that prevented the export of water from many counties in the Sacramento Valley of California (Hanak [11]).

A formal quantitative specification of the decision to adopt water market institutions is shown in Howitt [13]. Unlike the spatially-based analysis earlier in this chapter where surface water cost is a function of distance from the source, the approach taken by Howitt defines the optimal timing of institutions over a uniform set of water market opportunities. The value of a water market is defined as depending on the state variable which characterizes the gains from trade in water from the difference between value marginal products (excess demand) within the potential market. This state variable is defined as a stochastic continuous time Ito process which when combined with a Weiner process, leads to more manageable differential equations describing the change in social value of the resource. The optimal switch time for establishment of the market institution is characterized by two sets of dynamic first order conditions, the value matching and smooth pasting conditions. The value matching position states that at the optimal switch point, the expected present value of the flow of costs of unmet excess demands for water trades, minus the value of the option to switch in the future, must be equal to the lump sum institutional cost. The value of the option to switch in the future, which is given up by taking action in the establishment of an institution, is generally termed the hurdle rate for any discrete capital investment. This condition is in contrast to the standard marginal trade conditions, which do not take account of the cost of losing the option to switch in the future once the fixed financial and political costs of institutional establishment have been spent. The cost of the lost option to switch in the future will drive a further wedge between the optimal benefit and cost conditions derived in equation 12. Howitt uses some typical parameters from the California water market to calculate the average delay in the optimal establishment of a market due to the hurdle rate cost of market establishment. The results show that the average delay varies from 4 to 16 years depending on the stochastic properties of the excess demand driven by fluctuations in water supply and the discount rate of the alternative risk-free asset. These latter parameters affect the value of the option to switch in the future that is foregone by the decision to introduce an institution at a given time. This increase in the cost of market establishment due to uncertainty, fixed costs, and irreversibility, further emphasizes the point made earlier, that as the transaction costs of a water market institution are reduced, the probability that the market institution will be adopted increases.

5.3 Institutions and Methods to Reduce Water Market Transaction Costs

Several economic historians have pointed out that land allocation by the Homestead Act was initially ineffective on the treeless western prairies and ranges due to the impossibility of building fences out of local timber. While settlers had clear and legal title to their land, it was ineffective as an incentive to develop crop farming, due to the excessive costs of effective fencing in many treeless parts of the high plains. It was not until the development and perfection of barbed wire in 1874 by Joseph Glidden that agriculture became a practical alternative to ranching in the fertile planes of the Midwest (Hornbeck [12]).

So rapid was the adoption of barbed wire that Glidden was not prepared for the response. Hornbeck recounts that when Glidden received an order for a hundred tons of barbed wire he was dumbfounded and telegraphed the purchaser asking if his order should not read 100 pounds. The order was in tons not pounds. In addition, the price of barbed wire dropped substantially from $20 per hundred pounds in 1874 to $1.80 per hundred pounds in 1897 further stimulating its widespread adoption. The enclosure of farmland on the High Plains was met with opposition from ranchers which initially resulted in destruction of some fences, however by 1880 this new way of enforcing property rights was reluctantly accepted by the common property interest groups. This example illustrates the role that transaction costs of defining, monitoring, and enforcing may play in controlling groundwater extraction. Without accepted and enforced measurement there can be no property rights or trade, so economizing on the implementation cost of these institutions is the key to their more widespread adoption.

Many economic analyses of water markets are predicated on, either fully defining property rights for groundwater in quantitative terms, or a conceptually optimal set of Pigouvian taxes to internalize the user cost of groundwater extraction. The first of these institutions requires the adjudication and allocation of pumping capacity of a given basin. If the basin is to be used correctly as a capital asset whose scarcity value fluctuates with the climate, groundwater pumpers must be able to optimally draw down on this asset in times of drought without incurring excessive pumping costs or, more importantly, buffer stock costs of lost wells. This optimal drawdown function of groundwater is essential in most Mediterranean climates but requires flexible institutions to allow optimal asset use without imposing externalities on other users. Many advocates of groundwater management presume that without full adjudication of the basin and allocation of full property rights in quantitative terms such management cannot take place. This desire for full adjudication basins before management is a serious impediment to its implementation given the costs and incredible time delays of basin adjudication. In California, for example, the adjudication of the waters of the Klamath River basin was finally settled in 2013 after 38 years in which it was under legal dispute. The cost was extraordinary, but the delay of 38 years in resolving the case was even more remarkable.

There is however a very effective alternative institution for groundwater management and marketing that does not require any regulation of pumping or legal adjudication of the existing groundwater. It is essentially a "cap and trade" method for allocating groundwater, and has been successfully implemented in Orange County California for the past 40 years and probably in many other parts of the West. The essential idea is that all that is required is the measurement of the quantity of water pumped and a determination of the average hydrologic safe yield to the basin. Given these two pieces of information, groundwater users are allowed to pump whatever quantity they wish, subject to the condition that they pay the replacement costs of the groundwater if they exceed their share of the average safe yield of the basin. The average safe yield quantity is prorated across overlying land owners in accordance with the correlative groundwater rights to the aquifer. This is essentially a "cap and trade" solution to groundwater institutions given that there are no Pigouvian costs, fines, or charges levied.

In the case of Orange County there have, for most years, been adequate supplies of expensive but available recharge water. The cost of recharge water effectively sets the price on replacing any pumping above a landowner's share of the average safe yield of the basin. However in many basins where outside sources of recharge are either unavailable, or it is too costly to inject into the groundwater aquifer, users who pump more than that prorated share will have to purchase additional shares of water from their neighbors at the opportunity cost. This institution is so simple and clear that the equity of the system is apparent to all users, and the transaction costs of its implementation are those of measuring groundwater extraction and enforcing the recharge cost. An advantage of the institution is that the cost of replacing excessive pumping is internalized in the system. Orange County has successfully managed three major droughts since the implementation of this groundwater institution, each time drawing down the aquifer to substitute for shortage of surface water supplies and increased evapotranspiration demand. In each instance the water management agency has successfully recharged the aquifer and restored groundwater levels after the drought was over. In addition, Orange County has a potential problem of seawater intrusion into the aquifer if a preventive mound of water is not maintained along the coastal strip. The maintenance of this mound is achieved by the differential pricing of groundwater and surface water. The cost difference encourages those pumpers along the coastal strip to substitute cheaper surface water for groundwater in this special area, and thus maintains the integrity of the aquifer over a long period of time.

Just as barbed wire revolutionized the transaction costs of enforcing property rights in the High Plains, cheap and consistent measurement of total water use, and by inference, groundwater use by remote sensing sources from satellites offers an alternative to the costly and politically difficult process of on the ground monitoring and measurement of wells, capacities, and water use.

Over the past 15 years a line of research has concentrated on using the energy information from the Landsat satellite to estimate net water consumption. The researchers have been able to use six bands of thermal energy readings at a 40 m^2 pixel basis to calculate the net evapotranspiration on a pixel-by-pixel basis for each two weekly pass of the satellite. This research has, in the US, advanced most rapidly in the state of Idaho, driven by researchers at the University of Idaho (www.idwr.idaho.gov/GeographicInfo/METRIC/et.htm). Such is the acceptance of the system in the State of Idaho that several cases of water curtailments in 2009 and disputes over water rights in 2006 have been settled on the basis of remotely-sensed data measurements. These decisions by the director of the Idaho Department of Water Resources have been adjudicated and verified up to the High Court of the state. In addition to the greater accuracy and frequency of remotely-sensed evapotranspiration data, the costs of measurement by remote sensing in Idaho the results have been shown to be one third of the cost of those achieved by on-site visits. The system which is called Metric is now being applied in several Western states, and promises over time to significantly reduce the cost of monitoring water use in agriculture by increasing its precision.

A test of a similar system called SEBAL was performed for the California Delta by Medellìn-Azuara and Howitt [14]. They explored the potential of remote sensing technology using the Surface Energy Balance Algorithm for Land (SEBAL) method (Bastiaanssen et al., [4]) to provide an accurate estimate of consumptive use of water in crop production on five islands in the Sacramento San Joaquin Delta. The SEBAL-based dataset on energy based measures of evapotranspiration for year 2007 were compared to evapotranspiration (ET) estimates using methods from the Irrigation Training and Research Center (ITRC) of California Polytechnic State University-San Luis Obispo. The ITRC measurements were based on a spreadsheet approach that extrapolated the results of field trials. A second method used to compare the SEBAL measurements was developed by the California Department of Water Resources this approach is called the SIMETAW model. SIMETAW uses historical climate data to determine a daily soil water balance for individual cropped fields within a watershed region having one set of reference evapotranspiration (ETo) estimates. The alternative approach uses historical climate data and batch files of soil and climate data to perform daily soil water balance for individual cropped fields, for 20 crops, and 4 land-use categories over the period of record by combinations of detailed analysis.

The results showed that the SEBAL-based remotely sensed estimates of evapotranspiration were more precise and consistent than those based on field measurements and spreadsheet extrapolations. However, the main advantage of remote sensing is that it removes the need for costly and intrusive ground measurement, and has a consistent and legally justifiable basis for the measurement of total net water use and thus net groundwater use. If adopted on a statewide basis, similar remotely-sensed water measurement methods should significantly reduce the transaction costs of managing water and water markets and thus possibly play the role that barbed wire played in implementing landowning institutions on the High Plains.

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