Workshop in Political Theory and Policy Analysis

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Colloquium Presentation
November 16, 1992

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The Workshop in Political Theory and Policy Analysis combines teaching, research, and related activities where faculty, visiting scholars, and students have opportunities to participate in productive scholarship. The term "workshop" is used to emphasize a conviction that research skills are best acquired where students and faculty, working as apprentices and journeymen, participate in the organization and conduct of research.

Dr. Michael R. Moore, Economic Research Service, USDA, Washington, DC, will be the speaker for the Workshop Colloquium on Monday, November 16, 1992. **His presentation is entitled "Rent Appropriation and Groundwater Property-Right Systems in the American West: A Strategic and Laboratory Analysis." An abstract of his paper [co-authors Roy Gardner and James M. Walker, Department of Economics, Indiana University] is provided below.**

This paper considers the issue of rent appropriation from a groundwater common property resource under various property-rights systems employed by states in the American West. A benchmark model is constructed with a fixed stock of groundwater and fixed exhaustion time, with a specification based on data from the Ogallala Aquifer. Solving this model for its efficient equilibrium and a subgame perfect equilibrium provides a calibration for comparing rent appropriation from different property systems. The subgame perfect equilibrium accords closely to Texas state law. Among the systems compared are the prior appropriation doctrine (used by most western states), the correlative rights doctrine (adopted in Nebraska, Oklahoma, and some groundwater basins in California), the Arizona Groundwater Management Act of 1980, and the Smith Rule (a rule proposed by Vernon Smith in 1977 for use in Arizona). Each system varies in the nature of aquifer entry rules, individual withdrawal permits, and minimum time-to-exhaustion rules. The paper: (1) models these features as parametric traits of property systems, (2) analyzes individual strategic behavior within this framework, and (3) reports results from laboratory experiments that apply the framework. As states consider groundwater policy reform, the analysis of actual property-rights systems and parallel laboratory results can inform the policy process.

A copy of his paper is available by calling the above telephone number. Colloquium sessions begin at 12 noon and adjourn promptly at 1:30 p.m. You are welcome to bring your lunch. Coffee is provided free of charge, and soft drinks are available. We hope you will be able to join us!

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Rent Appropriation and Groundwater Property-Right Systems in the American West: A Strategic and Laboratory Analysis

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Rent Appropriation and Groundwater Property-Right Systems in the American West: A Strategic and Laboratory Analysis

1. Introduction

Between the poles of rent maximization and complete rent dissipation, wide latitude exists for institutions to manage or allocate common property resources (CPRs) with reasonable economic performance. Two topics addressed in previous research are salient. One concerns the role of limiting entry by agents into a commons. In the seminal article on the economics of CPRs, Gordon (1954) described how monopolist ownership would remove GPR externalities, thereby creating incentives for rent maximization. Eswaran and Lewis (1984), applying a model of a CPR as a time dependent repeated game, derived a related analytical result that the degree of rent appropriation depends inversely on the number of agents depleting the resource. In the context of groundwater, Brown (1974) and Gisser (1983) reasoned that existing laws restricting entry into groundwater CPRs would improve rent appropriation. Empirical experience with more than five agents, however, reached pessimistic conclusions in two cases. Libecap and Wiggins (1984) found that cooperative behavior in oil pool extraction occurred only with fewer than five firms. Otherwise, state law was required to coerce cooperation with roughly 10-12 firms. Indeed, with hundreds of firms operating in the East Texas oil fields there was no cooperation and, apparently, complete rent dissipation. Walker, Gardner, and Ostrom (1990) and Walker and Gardner (1992) reached a similar conclusion in analysis of data from laboratory experiments on noncooperative game CPRs. A high degree of rent dissipation or a high probability of resource destruction occurred even with access limited to eight agents.[1]

The second topic concerns the ability of additional regulations or property rights, other than entry restrictions, to mitigate CPR externalities in light of noncooperative behavior. With variation in regulations across three states serving as a natural experiment, Libecap and Wiggins (1985) concluded that regulations encouraging oil field unitization increased economic efficiency of extraction. A federal regulation operating on the public lands of Wyoming empirically outperformed an Oklahoma regulation, which outperformed a Texas regulation. The federal regulation granted quite favorable lease terms if firms agreed to unitize their leases. The Oklahoma and Texas laws required 63 percent and 100 percent agreement of operators, respectively, to invoke unitization. Forms of property rights, such as firm-specific fishing rights or quotas (e.g., Levhari, Michener, and Mirman 1981), also are widely recognized as reducing or removing the incentive for a race to exploit a CPR. Specific to groundwater, Smith (1977) recommended that rights to a share of the groundwater stock should replace Arizona's then-existing rule of capture, while Gisser (1983) noted that New Mexico's individual rights to annual water quantities, combined with a guaranteed time period of depletion, effectively define a share right in the stock. Both reasoned that these property rights would go far toward achieving efficient groundwater depletion.

State governance of groundwater resources in the western United States provides a natural institutional setting to study the effect of property rights and regulations on rent appropriation. In the early- to mid-1900s, independent state authority over groundwater resulted in adoption of four distinct legal doctrines governing groundwater use in the 17 western states (Sax and Abrams 1986; Smith 1989). Each doctrine establishes a set of principles directing entry and allocation rules. Further, concern about the pace of groundwater mining has spawned major legal reforms in five states within the last twenty-five years.[2] The reforms primarily involved adopting specific regulations that either limit entry into groundwater basins to only the current groundwater pumpers or define permit systems setting quotas on individuals' annual pumping levels, or both. The variety across states of general doctrinal principles and specific regulations creates a diverse set of groundwater property-right systems in the American West.

This paper develops and empirically applies a general modelling framework of western groundwater property-right systems. Section 2 qualitatively describes the modelling framework in terms of externalities present in a groundwater commons and the ability of important attributes of the various state systems to remove or mitigate the externalities. In section 3, we model groundwater depletion from a non-rechargeable aquifer as a noncooperative game following the literature on CPRs as dynamic games (Levhari and Mirman 1980; Eswaran and Lewis; Reinganum and Stokey 1985). Section 4 links the institutional elements and the model to create an experimental design for evaluation. To implement the framework empirically, section 5 applies evidence from laboratory experiments to evaluate the relative performance of the various property-right systems, where the number of agents is varied. Performance is measured as the percentage of maximum rent appropriated. Given the high cost and imprecise measurement that confronts collection of field data, laboratory experiments offer a unique method for assessing the performance of various groundwater property-right systems[3] and the applicability of game theory to behavior in such systems.

2. CPR Externalities and Western Groundwater Property-Right Systems

This section describes the externalities present in a groundwater CPR and, then, links the externalities to key features and common elements of the various groundwater property-right systems. Producers depleting a CPR typically face three externalities (Eswaran and Lewis; Reinganum and Stokey; Negri 1990): a strategic externality, which occurs when only resource use establishes resource ownership; a stock externality, which occurs when current resource depletion increases future depletion costs; and a congestion externality, which occurs when one producer's current effort directly reduces the current output of another producer.

Groundwater depletion for irrigated agriculture creates the potential for all three externalities. Producers engaged in irrigated agriculture dominate groundwater use. Over the Ogallala Aquifer in the Great Plains region, for example, individual producers invest in deep wells drilled into the aquifer formation. Average depth-to-water in the Great Plains states in 1988 ran from 70 to 154 feet (U.S. Department of Commerce)" The strategic externality occurs in this situation because, under some groundwater doctrines, water use is the only vehicle to establish ownership. The stock externality occurs because, with groundwater pumping costs, individual water depletion reduces the aquifer's water-table level (with a time lag), thereby increasing everyone's future pumping costs. The congestion externality occurs by spacing wells too closely together, with a subsequent direct loss in pumping efficiency. (The congestion externality will not be discussed or modelled further. Virtually every western state has a well-spacing statute to avoid this externality. Further, well spacing is less interesting in a modelling context because it does not require a dynamic model (Negri 1989).)

The problem that groundwater poses is to create institutions, in particular property rights, that provide incentives for efficient intertemporal depletion of groundwater stocks. The rent-maximizing depletion path, given a stock externality and a non-rechargeable aquifer, is for the groundwater stock to decline over time at the optimal rate. Along suboptimal paths, the rate of decline is typically too fast. Time-dated property rights allocated among a set of producers could, in principle, satisfy the problem of efficient institutions.

Description of a state's groundwater property-rights system includes the general legal doctrine applied, combined with distinctive regulations adopted by the state.[5] The authoritative source on water law (Sax and Abrams) defines the four groundwater legal doctrines applied in the West as:

> *Absolute Ownership Doctrine:* The "absolute ownership rule was that the landowner overlying an aquifer had an absolute right to extract the water situated beneath the parcel. No consideration was given to the fact that the groundwater extracted from one parcel might have flowed to that location from beneath a neighbor's property..." (p. 787)
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> *Reasonable Use Doctrine:* As a minor modification of the absolute ownership rule, the "reasonable use rule may have curtailed some whimsical uses of groundwater that harmed neighbors, but it continued the basic thrust of the absolute ownership rule that treated groundwater as an incident of ownership of the overlying tract." (p. 792)
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> *Correlative Rights Doctrine:* "The central tenets of the doctrine... are [that:] (1) the right to use groundwater stored in an aquifer is shared by all of the owners of land overlying the aquifer, (2) uses must be made on the overlying tract and must be reasonable in relation to the uses of other overlying owners and the characteristics of the aquifer, and (3) the groundwater user's property right is usufructuary." (p. 795)
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> *Prior Appropriation Doctrine:* "As with surface streams, states that follow prior appropriation doctrine in regard to groundwater protect pumpers on the basis of priority in time... Most jurisdictions which employ the prior appropriation doctrine to groundwater protect only 'reasonable pumping levels' of senior appropriators." (p. 794) Further, again adopting a principle of the surface water appropriation doctrine, an appropriative right is established by demonstrating use of the water rather than being incidental to landownership.

Of the seventeen western states, twelve use the appropriation doctrine to establish basic principles of groundwater rights.[6] Texas is the only state to continue with the absolute ownership doctrine, the common-law doctrine adopted from English law. Nebraska and Oklahoma utilize general principles of the correlative rights doctrine. Arizona, a state with the reasonable use doctrine until recently, replaced existing law with the 1980 Arizona Groundwater Management Act. The Act primarily uses principles from the correlative rights doctrine in that water scarcity is shared "equitably" among landowners. Groundwater management occurs at the local level, rather than the state level, in California. There, several local basins utilize the correlative rights doctrine.

The absolute ownership doctrine provides a benchmark for studying groundwater property-right systems. As applied in its pure form in Texas, the doctrine institutes open access to an aquifer by granting an unlimited water right to an overlying landowner of any size. Absolute ownership thus serves as the doctrine most likely to stimulate full rent dissipation.

Other groundwater property-right systems are modelled as overlaying institutional constraints on the benchmark system. Three elements are important in characterizing different systems: the number of producers in the commons, the quantity nature of the property right, and the temporal nature of the property right. Table 1 provides an overview of the groundwater property-right systems in terms of these elements; refer to it for the remainder of this section.

First, consider the number of agents with access to groundwater. Since the concept of monopolistic ownership or unitary behavior does not apply to groundwater,[7] limited entry to the commons primarily should mitigate, as opposed to remove, the strategic and stock externalities. The four doctrines currently present in law imply different access rules. The prior appropriation doctrine gives chronologically senior pumpers security in the maintenance of "reasonable" depths-to-water (Grant). "Reasonable" does not preclude aquifer mining, i.e., it does not preserve a fixed depth-to-water.

It does place a presumption that, at some point, a state administrative agency will restrict additional entry to a groundwater CPR (Bagley; Grant). Groundwater users have successfully sued under the appropriation doctrine to block entry (Nunn). Like the absolute ownership doctrine, the reasonable use and correlative rights doctrines grant entry to the commons solely on the basis of ownership of overlying land (Sax and Abrams). Entry thus is more restrictive under prior appropriation than under the other doctrines.

Second, consider the way in which different doctrines and state laws define the annual quantity dimension of a groundwater right. The absolute ownership and reasonable use doctrines effectively define a rule of capture (Sax and Abrams). With these doctrines, land ownership conveys a right to extract the water from below a tract of land without regard to the interests of neighboring landowners. In contrast, the prior appropriation and correlative rights doctrines establish annual quotas on the quantity of a groundwater right. Western states implement these two doctrines via permit systems that specify individual quotas. The correlative rights doctrine "equitably apportions the supply among overlying landowners" (Tarlock, p. 1754). In practice, Nebraska and Oklahoma implemented versions of the correlative rights doctrine that set permit levels based strictly on an individual's share of the land overlying the aquifer (Aiken; Jensen). The prior appropriation doctrine, in contrast, sets permit levels solely on the basis of a pumper's historical use of water. The appropriative right is proscribed by the condition that water must be put to a "beneficial use" (Sax and Abrams, p. 794).[8] Note that, holding acreage constant, correlative rights are symmetrical because of equitable apportionment, while appropriative rights may be modelled as asymmetrical because early appropriators often have larger rights than later appropriators.[9] Quota-based permit systems, like entry restrictions, should tend to mitigate the strategic and stock externalities by establishing a measure of tenure certainty in a'water right.

Third, consider three ways in which time may enter the definition of groundwater property rights. To begin with, several states with permit systems also define a minimum time period before exhaustion could occur. Individual annual quotas translate into an aggregate annual quantity constraint. With information on the stock of water in an aquifer, the state agency thus can set the individual permits to guarantee a minimum depletion period, i.e., a year through which water in the aquifer is guaranteed. For example, New Mexico designated a minimum 40-year life to some aquifers (Gisser; Nunn), while Oklahoma set the year 1993 as a guaranteed year through which an aquifer's water would be available (Jensen).[10]

The case of Arizona illustrates the second way in which time can affect the definition of a right. As time elapses, Arizona periodically constricts the annual quota of every permit. In 1980, the Arizona Groundwater Management Act defined blocks of 10 years during which an individual's maximum depletion quantity would be fixed (Arizona Department of Water Resources). At the end of the decade, the quantity would then be reduced to a rate that would subsequently hold for the next decade. This would repeat from 1980 to 2020, with the goal of achieving a steady state of withdrawal equal to recharge by 2025. In effect, this type of mandatory water conservation sets out a block-declining depletion path for the pertinent Arizona aquifers.

Finally, a third way in which time can enter a groundwater right is by defining property shares in the groundwater stock. The stock share is effectively *timeless* because depletion of the share can occur at the owner's discretion, i.e., the right is silent in terms of an annual quota. A system of stock shares is termed the Smith Rule after its first proponent (Smith

1977). While no western state allocates groundwater with the Smith Rule, economists have speculated that it would mitigate most of the intertemporal inefficiency of groundwater depletion (Smith 1977; Anderson, et al.).

In terms of externalities creating inefficiency, the Smith Rule removes the strategic externality but ignores the stock externality. That is, it ends the strategic race to capture a share of the stock, but continues the incentive to capture a *cheap* share. Experimental study of the Smith Rule thus isolates the stock externality for independent study. In contrast, the first two ways in which time enters a groundwater right are not designed, in practice, to correct particular CPR externalities. Instead, these features should tend to mitigate the strategic and stock externalities, again by establishing a measure of tenure certainty in a water right. The model of the next section and the laboratory experiments based on the model will illuminate these issues further.

3. Modelling Groundwater Externalities as a Noncooperative Game

This section models a groundwater commons and the underlying CPR externalities, with the optimal solution characterized first and noncooperative game solutions characterized second. Key assumptions in the model are based on experience in the western states of mining deep aquifers for irrigated agricultural production. Consider a groundwater aquifer described by the state variable depth to water at time t, x(t). There are n agricultural producers using the water, with aggregate withdrawal rate equal to $\dot{x}(t)$,

$$\dot{x}(t) = \sum_{i=1}^{n} \dot{x}_i(t), \qquad (1)$$

where $\dot{x}$ denotes the time derivative and i indexes the producers. Equation (1) assumes no recharge, so that the model depicts water mining. Hereafter, we suppress the time notation when no confusion will result.

Water pumped to the surface is used in agricultural production. The instantaneous benefits, in dollars, accruing to producer i, $B_i(\dot{x}_i)$, are quadratic:

$$B_i(\dot{x}_i) = a\dot{x}_i - b(\dot{x}_i)^2, \qquad a, b > 0. \tag{2}$$

This assumption accords with production experience from aquifers like the Ogallala Aquifer (Kim, et al. 1989). Producers are assumed homogeneous, so that (2) applies to each i.

On the cost side, the instantaneous cost of pumping water to the surface, $C_i(\dot{x}_i, x)$, depends on both depth to water and rate of withdrawal:

$$C_i(\dot{x}_i, x) = (C_0 + C_1 x)\dot{x}_i, \qquad C_0 \geq 0,\ C_1 > 0. \tag{3}$$

(3) represents a stock externality in extraction costs. The greater the depth to water, the more it costs every producer to withdraw water. Given the common pool nature of the groundwater, an incentive exists for each producer to pump the relatively cheap water near the surface before other producers pump it. Equation (3) also specifies constant returns to scale in pumping, as cost depends linearly on the withdrawal rate. This again accords with aquifer experience.

Imagine an authority with total control over pumping. To maximize net benefits from groundwater depletion over a planning horizon of length T requires the solution to

$$\max \int_0^T \sum_{i=1}^{n} [B_i(\dot{x}_i) - C_i(\dot{x}_i, x)]\, dt \tag{4}$$

subject to x(0) given. Equation (4) assumes no discounting of net benefits, an assumption which is satisfactory for T not too large.[11] From (2) and (3), equation (4) simplifies to

$$\max \int_0^T [a\Sigma \dot{x}_i - b\Sigma (\dot{x}_i)^2 - (C_0 + C_1 x)\Sigma \dot{x}_i]\, dt. \tag{5}$$

By symmetry, $\dot{x} = n\dot{x}_i$, so that (5) becomes

$$\max \int_0^T [a\dot{x} - b(\dot{x})^2/n - (C_0 + C_1 x)\dot{x}]\ dt. \tag{6}$$

Finally, for (6) to have a positive solution, i.e., for groundwater depletion to be beneficial for the first unit of water withdrawn, the following joint condition on the parameters must hold:

$$a - C_0 - C_1 x(0) > 0 .$$

The Euler equation is a necessary condition for the maximization of (6). Letting $F = a\dot{x} - b(\dot{x})^2/n - (C_0+C_1x)\dot{x}$, this is

$$\frac{d}{dt}\frac{\partial F}{\partial \dot{x}} = \frac{\partial F}{\partial x} . \tag{7}$$

Under the linear-quadratic specification of net benefits, (7) leads to a second-order linear differential equation:

$$-\frac{2b}{n}\ddot{x} - C_1\dot{x} = -C_1\dot{x} . \tag{8}$$

Because equation (8) simplifies to $\ddot{x} = 0$, the optimal solution, x^*, is a linear function of time, $x^* = K_0 + K_1 t$.

A second necessary condition for the maximization of (6) is the transversality condition:

$$\frac{\partial F}{\partial \dot{x}}(T) = 0 \ . \tag{9}$$

Transversality here implies that the last unit of water withdrawn has marginal net benefit of zero, and that this last unit be withdrawn at time T. Again using (2) and (3), equation (10) creates a terminal condition of

$$\dot{x}(T) = \frac{a - C_0 - C_1 x(0)}{2b/n + C_1 T} \ . \tag{10}$$

The terminal condition together with the initial condition, x(0), serve to identify the constants K_0 and K_1 of the optimal time path:

$$\begin{aligned} x^*(0) &= K_0 \\ \dot{x}^*(T) &= K_1 \ . \end{aligned} \tag{11}$$

Thus, the optimal depth to water at time t is given explicitly by

$$x^*(t) = x(0) + \frac{a - C_0 - C_1 x(0)}{2b/n + C_1 T} t \ , \tag{12}$$

with each producer withdrawing water at the uniform rate

$$\dot{x}_i^* = \frac{a - C_0 - C_1 x(0)}{2b + C_1 T n} \ .$$

Notice that the optimal withdrawal rate for a producer depends on the number of producers. This reflects the stock externality present in the problem.

Substituting (12) into (6) characterizes the optimal value of rent available from groundwater depletion, V, as

$$V = K_1 T \ [a - \frac{b}{n} K_1 - C_0 - C_1 K_0 T - \frac{C_1 K_1 T}{2} \ ] \ . \tag{13}$$

V is the efficiency standard by which all other withdrawal paths are measured. Let $\dot{w}$ be any other withdrawal rate with attendant value W. We define the efficiency of $\dot{w}$ to be the ratio W/V. This ratio lies between 0% and 100%, and expresses the degree to which the groundwater resource's maximum rent is actually appropriated.

This paper is especially interested in withdrawal patterns associated with game equilibria. In a noncooperative game, as opposed to an optimal solution, each producer maximizes own net benefit without regard to the effect of this behavior on other producers. This is the strategic externality (Negri 1990). Let $F_i(\dot{x}_i,x) = B_i(\dot{x}_i) - C_i(\dot{x}_i,x)$ denote individual producer net benefits. In contrast to (4), each producer now solves

$$\max \int_0^T F_i(\dot{x}_i, x)\, dt \; , \tag{14}$$

again subject to x(0) given.

The Euler equation for a game equilibrium solution is analogous to that for an optimal solution:

$$\frac{d}{dt}\frac{\partial F_i}{\partial \dot{x}_i} = \frac{\partial F_i}{\partial x}, \tag{15}$$

which here implies

$$-2b\ddot{x}_i - C_1 n\dot{x}_i = -C_1\dot{x}_i , \tag{16}$$

using equation (1) and symmetry. Rearranging (16) yields

$$\frac{\ddot{x}_i}{\dot{x}_i} = \frac{C_1(n-1)}{-2b}. \tag{17}$$

Note that in contrast to the optimal solution (except when $n = 1$ and the game is degenerate), the time path of withdrawal is no longer linear, but strictly concave according to (17) with $\dot{x}_i > 0$ and $\ddot{x}_i < 0$. The more producers in the commons, the greater is the concavity. Thus, a game equilibrium withdrawal path is suboptimal, with water depletion occurring more rapidly than optimal. This is a consequence of the rule of capture defining groundwater property rights.

A game equilibrium must also satisfy a transversality condition like (9). However, since these equilibria are not optimal, the transversality condition can be satisfied at any time t:

$$\frac{\partial F_i}{\partial \dot{x}_i}(t) = 0. \tag{18}$$

Equation (18) again manifests inefficiency. The time t in (18) marks the date at which the economically useful water is exhausted. According to (15), earlier exhaustion Indicates a relatively more inefficient use of the economically available water. Thus, we can interpret the game equilibria which satisfy (17) and (18) as water races, where the time to exhaustion depends on which equilibrium path producers follow.

The efficiencies achieved at a game equilibrium can run anywhere from near 0% to almost 100%, depending on the exhaustion date. This multiplicity of equilibria raises the question: which equilibrium will be observed, one at which the exhaustion date is early or late? The motivation for this study is to shed light on these questions, and to assess how seriously the various commons externalities are likely to impact groundwater depletion and agricultural production in the western United States.

4. Experimental Design

This section parameterizes the noncooperative game that forms the basis of all the experiments conducted. It also overlays the institutions associated with the several western groundwater property-right systems onto the baseline game. Theory suggests the following treatment variables: number of producers, constraints on withdrawal rates, and minimum time to exhaustion (see Table 2). Let n denote the number of producers, as before. Let $w_i(t)$

denote a quota on producer i's withdrawal at time t, and T^m denote the minimum time to exhaustion. The constraints $w_i(t)$ are calibrated to fit the various doctrines that employ them. The guiding design principle in all patterns of constraints is that the optimal solution must be feasible according to the constraints.

We operationalize the various groundwater property-right systems as follows. First, n can take either the values 5 or 10, with n — 5 reflecting the effect of a prior appropriation doctrine's restriction on access. Next, we set $T^m = 0$ when there is no minimum time to exhaustion; otherwise we set $T^m = 5$ to reflect the minimum time to exhaustion, as is found in the New Mexico appropriative right, the Nebraska correlative rights, Oklahoma correlative rights, and Arizona Groundwater Management Act of 1980.[12] In all designs, T = 20 is the economic lifetime of the resource; after this time, the experiment ends.

Theory suggests the following hypothesis regarding number of producers:

Hypothesis 1: An increase in n, *other things equal, reduces rent appropriation.*

For the optimal solution, as well as for all equilibrium solutions, x*(T) - x(0) represents the amount of economically valuable groundwater ultimately pumped from the aquifer. Call this quantity X. Following the Smith Rule, allocation of property rights to a share of the stock says that

$$\int_0^T \dot{x}_i(t) \leq \frac{X}{n}. \qquad (19)$$

Equation (19) guarantees each producer an equal share of the economically valuable water, along with the freedom to use water any time over the planning period. However, it does not guarantee producers cheap water. The Smith Rule generates

Hypothesis 2: *Property rights to a stock share increase rent appropriation.*

We also consider a variant of the Smith Rule with a minimum time to exhaustion, which may enhance efficiency empirically. To implement minimum time to exhaustion, we add the constraint that

$$\int_0^{T^m} \dot{x}_i(t) \leq \frac{X}{n}, \qquad T^m < T. \tag{20}$$

Equation (20) guarantees that water will remain at least until time T^m.[13]

As described previously, individual states implement laws defining a minimum time to exhaustion via constraint (20) independently of constraint (19) and the Smith Rule. This leads to a general hypothesis concerning this type of law:

Hypothesis 3: *An increase in minimum time to exhaustion, other things equal, increases rent appropriation.*

The annual withdrawal constraints for the correlative rights doctrine (Nebraska and Oklahoma versions) and the experimental variant of the generic prior appropriation doctrine are all set as:

$$\dot{x}_i(t) \leq w_i(t) = w. \tag{21}$$

In equation (21), w is set low enough that it constrains the worst equilibrium solution, but leaves the best equilibrium and the optimum unconstrained. This leads to the fourth hypothesis:

Hypothesis 4: *A decrease in the withdrawal constraint w increases rent appropriation.*

Indeed, setting w low enough would allow us to replicate the optimal path.[14]

The quantity and temporal characteristics of various groundwater rights do not guarantee the efficient depletion path. Nevertheless, the characteristics will tend to *remove* the strategic or stock externality in some cases, and to *mitigate* one or more externalities in other cases. By so doing, the characteristics will affect rent appropriated through depletion of the groundwater commons. Analytically, none of the treatments envisioned in hypotheses 1-4 will apply if producers actually play the best available game equilibrium.

Finally, we define two variants on single period withdrawal constraints. First, to model the generic prior appropriation doctrine, where users who are first in time often have greater rights than those who come later (Burness and Quirk), we set $w_1 > w_2$, with 2 producers bounded by w_1 (the early entrants) and 3 producers bounded by w_2 (the latecomers). Second, to model Arizona's block-declining annual permits, we use the same w_1 and w_2, only now w_1 refers to the first 5 periods and w_2 to the later periods. The final hypothesis is:

Hypothesis 5: Neither asymmetric withdrawal rights nor block-declining annual permits enhance rent appropriation.

All experiments use the following discrete approximation to the model. Time T is divided into 20 periods. Subject i makes a decision $x_i(t)$ in each period t, t = 1,2,...,20. The decision $x_i(t)$ is itself integer-valued with a lower bound of 0 and an upper bound, if any, given by the institutions. The units of the decision are called "tokens." Payoffs according to the net benefit function are evaluated at integer values of the arguments of that function.

All experiments satisfy the following net benefit function parameterization:

$a = 2.2 \quad b = 0.05 \quad C_0 = 0 \quad C_1 = .01 \quad x(0) = 1.$

These parameters generate the following optimal solution characteristics for the case $n = 10$:

$V = \$214.50 \quad X = 200 \quad \dot{x}_i^*(t) = 2.$

The case $n = 5$ gives a similar optimal value ($V = \$201$) and double the individual withdrawal rate ($\dot{x}_i^*(t) = 4$) to the nearest integer.

The sharpest contrast to these optimal values is provided by the worst game equilibrium, which occurs for $n = 10$. This equilibrium exhausts the water in the first period with values of $\dot{x}_i(1) = 21$ and $V = \$20.50$. It thus has an efficiency of \$20.25/\$214.50 = 9.4%. To the extent that subjects play the worst equilibrium, then any treatment that enables them to play a better equilibrium will display an efficiency higher than 9.4%. The worst game equilibrium for $n = 5$ is similar. Figure 1 plots various equilibrium time paths of withdrawal, as well as the optimal time path.

Table 2 summarizes the design treatments for the baseline and the five groundwater doctrines in terms of the (n, T^m, w) parameterization. Notice that the optimal solution is feasible in all treatments, and that the treatments constrain only very poor equilibria.

All experiments were conducted at Indiana University. Subjects were volunteers recruited from economics courses, paid in cash in private at the end of an experiment. No subject participated in more than one experiment. Subjects privately went through a series of instructions (available from the authors upon request) and had the opportunity to ask the person administering the experiment a question at any time. Each subject made a single decision each period, namely how many tokens to buy. A token represented a unit of water. All subjects made this decision simultaneously, subject to whatever constraints were present in the design they faced. Benefits and costs for each subject were then computed, and reported to that subject. Subjects were told that the experiment would last up to 20 periods. Subjects were also told if token costs ever reached a level at which buying a token would automatically lose them money, the experiment would end at that point. The next section presents and discusses the experimental results.

5. **Laboratory Results and Discussion**

6. Conclusions

THESE TWO SECTIONS AWAIT RESULTS FROM THE LABORATORY EXPERIMENTS

Footnotes

1. The result that fewer than five firms are necessary for cooperation has received theoretical support from Selten (1971).

2. The states are Arizona, Colorado, Kansas, Nebraska, and Oklahoma.

3. Several earlier articles addressed the relative performance of various groundwater institutions. The costliness of collecting data on groundwater use and the difficulty of applying game-theoretic models explains the reliance in that research on analytical results (Dixon; Negri 1989), simulation methods (Dixon), or reasoned institutional arguments concerning the desirable properties of specific groundwater property-right systems (Anderson, et al. 1983; Gisser; Smith 1977).

4. In the states overlying the Ogallala Aquifer, 1988 average depths-to-water in feet were: Colorado, 70; Kansas, 107; Nebraska, 72; New Mexico, 122; Oklahoma, 95; and Texas, 154 (U.S. Department of Commerce, p. 19).

5. Implementing the doctrines involves a combination of state law and state regulations. Many doctrines are specified in state constitutions. Administration of the law, though, has been accomplished through state agencies, with the attendant tendency to establish rules and regulations for groundwater property rights.

6. The twelve states are Colorado, Idaho, Kansas, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming (Grant 1981).

7. With groundwater, irrigation development proceeded via settlement of arable cropland by individual farm families. The conceptual artifice of sole ownership thus lacks sufficient realism to be incorporated into this groundwater model except as a benchmark. Further, unlike oil or natural gas, the economic value of water in agriculture cannot support transportation of groundwater to distant markets. This feature, together with the high cost of negotiation relative to resource value, removes the incentive for unitization of aquifers developed for agriculture. In contrast, unitization is an incentive that operates successfully in many cases for oil fields (Libecap and Wiggins 1984, 1985).

8. Both appropriative-right permits and correlative-right permits define an individual's maximum annual use rather than fixing a specific use level.

9. Burness and Quirk demonstrate the result of early appropriators establishing larger water rights than later appropriators for the case of surface water allocation via the prior appropriation doctrine.

10. The procedure applied in Oklahoma illustrates the implementation of a minimum time period before exhaustion under principles of the correlative rights doctrine. The Oklahoma Ground Water Law of 1972 translated explicit individual shares of the groundwater stock into annual quotas (Jensen, p. 465-471). Individual shares of the stock were allocated according to the individual ownership share of the land overlying the aquifer. This number of

acre-feet then was divided by the number of years between the implementation date (say, 1975) and the minimum exhaustion date (1993 for some Oklahoma aquifers) to obtain an individual's permitted maximum annual depletion rate.

11. The optimal solution and game solutions can easily be generalized to accommodate discounting without alternating the qualitative results. Discounting is not applied because the brief duration of a laboratory experiment (usually two hours) makes it difficult to implement empirically,

12. For Arizona, this reflects the earliest date at which groundwater pumping would equal recharge, not the minimum time to exhaustion.

13. Minimum time to exhaustion also could be implemented by constraining annual usage by a producer over the entire period, rather than overall usage. Equation (20) is used, however, because the states implement the minimum time to exhaustion as an overall usage constraint.

14. This is only because of the assumption of no discounting. Such a constraint could not by itself force the optimal solution in the presence of discounting.

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Table 1. Modelling Variation in Groundwater Property-Right Systems in the American West

Water-Use Quantities (Allocation among individuals)	Number of Players ($n_1 > n_2$) n_1	n_2	Minimum Time to Exhaustion Free	Fixed	Allocation Rule Among Individuals Equal	Unequal	Comments
(1) Benchmark: only n_1 exogenous	X		X		--No permits or quantity allocations--		(1) Generic absolute ownership doctrine; Texas.
(2) Stock Shares							(2)
(a)	X		X		X		(a) Basic Vernon Smith Rule.
(b)	X			X	X		(b) Experimental variant of (2)(a).
(3) Annual Quotas (annual quantity constraint)							(3)
(a)	X		X		X		(a) Nebraska model of correlative rights doctrine.
(b)	X			X	X		(b) Oklahoma model of correlative rights doctrine.
(c)		X		X		X	(c) Generic prior appropriation doctrine; New Mexico, Colorado.
(d)		X		X	X		(d) Experimental variant of (3)(c).
(4) Block-Declining Annual Permits							(4)
(a)	X			X	X		(a) Essentials of Arizona Groundwater Management Act of 1980; allocations decreased every 10 years.

Table 2. Parameterization of Western Groundwater Property-Right Systems for Laboratory Experiments				
Property-Right System	Number of Experiments	Number of Players (n)	Minimum Time to Exhaustion (T^m)	Water Use Quotas (w)[a]
Benchmark: Absolute Ownership (Texas)	3	10	0	∞
Smith Rule				
Base	3	10	0	$\Sigma_t\ \dot{x}_i(t) \leq 20$[b]
Variant	3	10	5	$\Sigma_t\ \dot{x}_i(t) \leq 20$
Correlative Rights				
Nebraska Variant	3	10	0	20
Oklahoma Variant	3	10	5	4
Prior Appropriation				
Base	3	5	5	8
Variant	3	5	5	$w_1 = 10;\ w_2 = 6$[c]
Arizona Groundwater Management Act of 1980	3	10	5	$w_1 = 10;\ w_2 = 6$[d]

[a] The quota for the Smith Rule states that accumulated multi-period water use cannot exceed a specified quantity. For the other experiments, the quota is a single-period constraint.

[b] $\dot{x}_i(t)$ represents individual decisions for i=1,...,10 and t=1,...,20.

[c] w_1 and w_2 represents two asymmetric classes of producers. Two producers are constrained by $w_1 = 10$ and three producers are constrained by $w_2 = 6$.

[d] w_1 and w_2 now represent quotas that decrease discretely at a certain period. Constraint w_1 holds for the first five periods (t=1,...,5) and w_2 holds for the last fifteen periods (t=6,...,20).