A Private Property Rights Regime to Replenish a Groundwater Aquifer

Bill Provencher

ABSTRACT. *Groundwater management is often reactive, and in some cases the groundwater stock (groundwater table) of an aquifer may fall below its optimal steady-state level before any thought is given to management. This paper examines a private property rights regime to restore a groundwater resource to its optimal steady-state. Results from a stochastic dynamic programming model of Madera County, California show that the private property rights regime recovers about 95 percent of the potential gain from groundwater management* (JEL Q25)

I. INTRODUCTION

Economists have long maintained that when a groundwater resource is common property, stock externalities induce an inefficient rate of groundwater pumping.[1] The remedy usually prescribed is central (optimal) control by a regulator, who uses taxes or quotas to obtain the efficient allocation of the resource over time. Smith (1977) and Anderson, Burt, and Fractor (1983) suggest an alternative institutional arrangement in which private shares to the groundwater stock are established.[2] Under this arrangement, a firm does not hold particular units of the groundwater stock, but rather the right to pump or sell a certain number of in situ units of stock whenever it chooses. A firm's consumption or sale of in situ stock reduces its share of the groundwater stock in a manner consistent with the state equation governing the groundwater resource; its share is increased via its entitlement to natural recharge and by the purchase of shares from other users. In many areas where central control is not politically feasible, this arrangement may offer a viable alternative. Moreover, as Anderson et al. suggest, it may provide firms with risk benefits not available under central control.

Unfortunately, groundwater management is often reactive, and possibly the groundwater stock in a given aquifer will be lower than its optimal steady-state level before any thought is given to management. In this situation a relevant question for economists is how to restore the groundwater stock to its optimal steady-state level. At first glance the private property rights arrangement described above appears ill-suited to the task because it involves an initial allocation of groundwater stock shares corresponding to the groundwater stock initially available for pumping. In the case where the groundwater stock is already too low, the initial allocation of stock shares is *negative* because the regulator wishes to restore the total groundwater stock to its optimal level. Firms would not be allowed to pump groundwater until their entitlements to natural recharge increased their stock shares—and by design, the difference between the actual groundwater stock and the optimal steady-state stock—to a positive amount.

Department of Agricultural Economics, University of Wisconsin, Madison.

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[1]Here the term "common property" refers to a resource exploited by a well-defined, finite set of firms, each of which freely chooses its rate of exploitation. As Bromley (1991) points out, a finite set of users may ultimately exploit a resource at the efficient rate by developing rules governing the use of the resource. Moreover, Dixon (1989) shows that even in a noncooperative setting, so-called trigger strategies may yield the efficient outcome. In this paper, attention focuses on the case usually examined in the literature on the economics of groundwater, where firms execute myopic pumping decisions (see, e.g., Kim, Moore, Hanchar, and Nieswiodomy 1989; Nieswiodomy 1985; Worthington, Burt, and Brustkern 1985; Feinerman and Knapp 1983; and Gisser and Sanchez 1980). In a groundwater basin with many users, this appears to be a reasonable approximation of behavior.

[2]Dudley (1988) examines this arrangement in the context of reservoir management, and refers to it as "capacity sharing."

Note, however, that a regulator may circumvent this problem, while still capturing the political and economic advantages of the private property rights arrangement, by initially allocating *all* groundwater stock as private shares and announcing that at a specified future date a particular number of stock shares—enough to ultimately prevent the groundwater stock from falling below the optimal steady-state level—will be reclaimed from each firm using the resource. Anticipating this action, firms would conserve stock shares to maintain their access to the groundwater resource *after* the regulator's reclamation of the announced number of shares. The corresponding path to the optimal steady-state would be a smooth one controlled by the price of groundwater stock shares. This is the institutional arrangement examined in this paper. The next section characterizes the arrangement in a simple, deterministic setting. In Section III, results derived from a stochastic, dynamic programming model of Madera County, California are presented. Results concern the case where the groundwater resource is at its common property steady-state level and water managers wish to increase the groundwater stock (groundwater table) via the private property rights regime. A few concluding remarks are offered in Section IV.

II. THEORETICAL CONSIDERATIONS

To motivate the empirical results of Section III, we begin by examining the private property rights regime in a continuous-time, deterministic setting. Suppose M firms exploit a "bathtub" type aquifer characterized by a flat bottom and perpendicular sides. These firms are identical in the sense that the net benefit of groundwater consumption at time t, $g(x(t), u(t))$, is the same for all M firms, where $x(t)$ is the stock of groundwater at time t, and $u(t)$ is the nonnegative extraction of groundwater at time t.[3] The stock of groundwater $x(t)$ enters the benefit function because it affects the cost of extracting groundwater. Following Negri (1989), let $g_u > 0$, $g_x > 0$, $g_{xx} < 0$, $g_{uu} < 0$, and $g_{ux} > 0$, where subscripts index partial derivatives. Given that the M identical firms pump groundwater at the same rate, the state of the groundwater stock is governed by the differential equation,

$$\dot{x}(t) = r - Mu(t), \qquad [1]$$

where r is the fixed flow of natural recharge.

Let x^* denote the optimal steady-state stock level, and let x_0 denote the initial level of the groundwater stock, with $x_0 < x^*$. The regulator initially grants each of the M firms s_0 groundwater stock shares, equal to $1/M$th of the initial groundwater stock. As a practical matter, each firm's groundwater stock shares represent its private stock of groundwater. The economic significance of this stock is that it constrains the pumping behavior of the firm; the firm can pump groundwater only if its private stock is positive. The firm's private stock changes over time, reflecting gains from natural recharge and losses from groundwater pumping, as well as gains and losses from the firm's activity in the market for groundwater stock shares. The *aggregate* private stock evolves according to state equation [1]; no groundwater enters the aquifer that does not accrue to the private stock of some firm, and similarly, no groundwater is removed from the aquifer that is not removed from the private stock of some firm. If on balance firms are conserving private stock, $x(t)$ increases over time.

The objective of the regulator is to raise the groundwater stock to the optimal steady-state level x^*. To this end, the regulator announces at time 0 its intention to reclaim x^* groundwater stock shares at time $T > 0$. Reclaiming x^* groundwater stock shares at time T reduces the aggregate private stock from $x(T)$ to $x(T) - x^*$.

[3] In this analysis, the groundwater consumed equals the groundwater extracted. In the programming model in Section III, this simplification is abandoned; much of the groundwater applied in irrigation returns to the groundwater aquifer.

More generally, for $t < T$ the aggregate private stock is $x(t)$, and for $t \geq T$ the aggregate private stock is $x(t) - x^*$. The regulator's problem is a timing problem; restricting the availability of stock shares too soon after the initial allocation of shares could lead to economic calamity, insofar as it would provide firms with little opportunity to mitigate the announced reclamation of groundwater stock shares by increasing their private stocks through conservation. The technical details of the firm's problem examined below ultimately support a simple logic about why firms are compelled to conserve groundwater stock shares in response to the anticipated reclamation of stock shares at time T. Suppose instead that all firms fail to conserve groundwater, and so the total groundwater stock does not increase as time T approaches. Then at time T all firms face economic disaster; they are denied access to the groundwater resource for as long as it takes to naturally recharge the groundwater resource to the level desired by the government. Now suppose one savvy firm recognizes that the price of groundwater stock shares will jump at time T as its neighbors suddenly find themselves without access to water. By initially hoarding stock shares, the firm reaps substantial speculative gains at time T by selling these shares to its less farsighted neighbors. Of course, where there is one savvy firm there are usually several, and the arbitrage activity of these firms yields a rational price of groundwater stock shares that sends a clear signal to all firms about the true scarcity of stock shares. This price induces all firms to conserve groundwater as time T approaches.

The Firm's Problem

The firm increases its private stock by purchasing stock shares and reduces its private stock by consuming groundwater or selling stock shares. Moreover, the firm's private stock is amended over time by its entitlement to natural recharge, and at time T the firm surrenders s^* stock shares to the regulator. In the symmetric case considered here, each firm receives $1/M$th of the natural recharge, and each firm surrenders the same amount of private stock at time T, $s^* = x^*/M$. Formally, we define a tracking variable s, such that for $t < T$, $s(t)$ defines the firm's private stock at time t, and for $t \geq T$, the expression $s(t) - s^*$ defines the firm's private stock at time t. This tracking variable evolves over time according to the differential equation,

$$\dot{s}(t) = \frac{r}{M} + z(t) - u(t), \quad [2]$$

where $z(t)$ is the firm's purchase of groundwater stock shares (a negative value if shares are sold).

The problem of the firm is complicated by its extramarket interaction with the other firms exploiting the groundwater resource. The pumping behavior of other firms affects the cost at which the firm can extract its private stock of groundwater. The firm knows this and in its pumping decision it anticipates the equilibrium feedback strategies of the other $M - 1$ identical firms. This is the model of behavior now commonplace in studies of the joint exploitation of natural resources (see, e.g., Eswaran and Lewis 1984; Negri 1989; Dixon 1989; and Toman 1986). So from the firm's perspective, the differential equation [1] can be restated,

$$\dot{x}(t) = r - (M - 1)u^{\varepsilon}(x(t), t, T) - u(t), \quad [3]$$

where $u^{\varepsilon}(x(t), t, T)$ is the equilibrium pumping strategy of each of the other $M - 1$ identical firms.

In the "grace period" preceding the regulator's reclamation of groundwater stock shares, the firm cannot pump more groundwater than it holds as private stock:

$$s(t) + \frac{r}{M} + z(t) - u(t) \geq 0, \quad t < T. \quad [4a]$$

After the regulator reclaims s^* stock shares, things get a bit more complicated. If the firm's private stock is negative—which is possible due to the loss of s^* stock shares—groundwater pumping is forbidden. On the other hand, if the firm's private stock is positive, then as before it cannot pump more groundwater than it holds. In light of the nonnegativity constraint $U(t) \geq 0$, these restrictions are captured by the constraint

$$u(t)\left[s(t) + \frac{r}{M} + z(t) - s^* - u(t)\right] \geq 0, \quad t \geq T. \quad [4b]$$

Let i denote the discount rate and let $p(t)$ denote the price of groundwater stock shares. Formally, the problem of the firm is to choose the control variable paths $u(t)$ and $z(t)$ to maximize the present value of net revenues,

$$\int_0^T e^{-it}[g(x(t), u(t)) - p(t)z(t)]\,dt + \int_T^\infty e^{-it}[g(x(t), u(t)) - p(t)z(t)]\,dt, \quad [5]$$

subject to state equations [2] and [3], the initial state values s_0 and x_0, the nonnegativity constraint $u(t) \geq 0$, and the inequality constraints [4].

The analysis is now restricted in several important ways. First, attention focuses on the case where the bottom of the aquifer is sufficiently deep that it is never economical to exhaust the groundwater resource. This appears to be typical for many groundwater basins in California. In this case, the common property steady-state stock level is positive, and so constraint [4a] is never binding; quite simply, firms hold more private groundwater stock than they would ever care to use due to the high cost of extracting the resource. Second, the analysis enlists the implicit assumption of many previous authors that firms are myopic with respect to the impact of their groundwater pumping on the state of the groundwater resource (see footnote 1 for references). Formally, this implies that in maximizing its welfare the firm does not explicitly recognize state equation [3]. Although the firm understands that the total groundwater stock changes over time, it fails to appreciate that its own groundwater pumping affects the total. This assumption is most appropriate when the groundwater resource is exploited by a large number of firms. Finally, attention focuses on the case where $u(t) > 0$, $t < T$. In general there exist cases where the equilibrium solution of the firm's problem includes $u(t) = 0$ for some $t < T$. However, this result arose in the programming model of Madera County (presented in the next section) only when the value of T was very low relative to the desired stock restoration, so that, in effect, the best strategy of firms to prepare for the reduction in their private groundwater stocks at time T was to not pump at all. Such a "forced march" to x^* usually has severe economic consequences, and insofar as the regulator chooses T to maximize the value of the groundwater resource (within the context of the private property rights regime), the assumption that $u(t)$ is always strictly positive for $t < T$ is a reasonable point of departure for deriving analytical results.

In light of the assumption that the firm does not recognize state equation [3] when solving its decision problem, the relevant current value Hamiltonian is

$$H = g - pz + \lambda\left(\frac{r}{M} - u + z\right), \quad [6]$$

where λ is the current value costate variable associated with state equation [2], and the arguments of functions are suppressed for the sake of clarity. For $t \geq T$, the usual Hamiltonian conditions for an optimum are modified to reflect the effect of the nonnegativity constraint $u(t) > 0$, and the inequality constraint [4b].[4] Letting γ denote the Lagrangian multiplier associated with [4b], the conditions for an optimum include,

$$g_u - \lambda = 0, \quad t < T; \quad [7a]$$

$$g_u - \lambda + \gamma\left(s + \frac{r}{M} + z - s^* - 2u\right) \leq 0,$$

[4] See, for instance, Kamien and Schwartz (1991). For $t < T$, the Hamiltonian conditions are the usual ones, because by assumption both [4a] and the nonnegativity constraint are nonbinding.

$$u\left[g_u - \lambda + \gamma\left(s + \frac{r}{M} + z - s^* - 2u\right)\right] = 0,$$

$$u \geq 0, \quad t \geq T; \quad [7b]$$

$$\lambda - p = 0, \quad t < T; \quad [8a]$$

$$\lambda - p + \gamma u = 0, \quad t \geq T; \quad [8b]$$

$$\dot{\lambda} = i\lambda, \quad t < T; \quad [9a]$$

$$\dot{\lambda} = i\lambda - \gamma u, \quad t \geq T; \quad [9b]$$

$$\gamma\left[u\left(s + \frac{r}{M} + z - s^* - u\right)\right] = 0,$$

$$u\left(s + \frac{r}{M} + z - s^* - u\right) \geq 0,$$

$$\gamma \geq 0, \quad t \geq T. \quad [10]$$

Manipulation of these conditions yields three important—albeit entirely expected—results. Substituting [8a] into [7a] gives

$$g_u = p, \quad t < T, \quad [11]$$

which indicates that the positive price of groundwater stock shares induces firms to reduce the rate of groundwater pumping from the myopic rate even before groundwater stock shares are reclaimed by the regulator.

Differentiating [8a] yields

$$\dot{\lambda} = \dot{p}, \quad t < T. \quad [12]$$

Substituting [8a] and [12] into [9a] gives the result that prior to the reclamation of groundwater stock shares, the price of groundwater stock shares rises at the rate of interest:

$$\frac{\dot{p}}{p} = i, \quad t < T. \quad [13]$$

Finally, after substituting [8b] into [9b], we know that at the steady-state (with $\dot{x} = \dot{\lambda} = 0$),[5]

$$p = \frac{1 + i}{i}\gamma\frac{r}{M}. \quad [14]$$

Recall that after time T, the aggregate number of groundwater stock shares held by firms is defined by the expression, $x(t) - x^*$. If at the steady-state the inequality constraint in [10] is binding (γ is positive) for one of the identical firms using the groundwater resource, it is binding for *all* firms, and $x(t) = x^*$. In this light, [14] implies that for the nontrivial case where p is positive at the steady-state, x^* is in fact the steady-state stock under the private property rights regime.

The rationality of firms assures that there does not exist a time t such that $x(t) > x^*$. The proof is by contradiction. Suppose such a t does exist; then there also exists a time k as shown in Figure 1, where $x(k) > x^*$, $\dot{x}(k) = 0$, and $\ddot{x}(k) < 0$. Quite simply, the groundwater stock evolves smoothly over time, eventually returning to the (stable) steady-state. Let $j > k$ denote the time at which the groundwater stock returns to the steady-state. At both time k and time j, $u = r/M$, because $\dot{x}(k) = \dot{x}(j) = 0$. Moreover, because $u(k) = u(j) > 0$, the condition $g_u = p$ must hold at both time k and time j (see Appendix A for clarification); firms pump groundwater until the marginal value of groundwater in production equals the price of groundwater stock shares. So in light of the assumption $g_{ux} > 0$, we have

$$p(k) = g_u(x(k), r/M) > g_u(x(j), r/M) = p(j),$$

which violates rationality. A rational firm can reap speculative gains by selling groundwater stock shares at time k and buying them back at time j. Similar reasoning yields the more general result that the groundwater stock never declines after an initial increase, though it may increase after an initial decline (see Appendix A).

The rationality of firms also assures that the steady-state stock level is not reached before time T. Once again the proof is by contradiction. Suppose there exists a time $k < T$ such that $x(k) = x^*$. Either $\dot{x}(k) < 0$, $\dot{x}(k) > 0$, or $\dot{x}(k) = 0$. The first two possibilities clearly imply the violation of the result

[5]From [1], $\dot{x} = 0$ implies $u = r/M$.

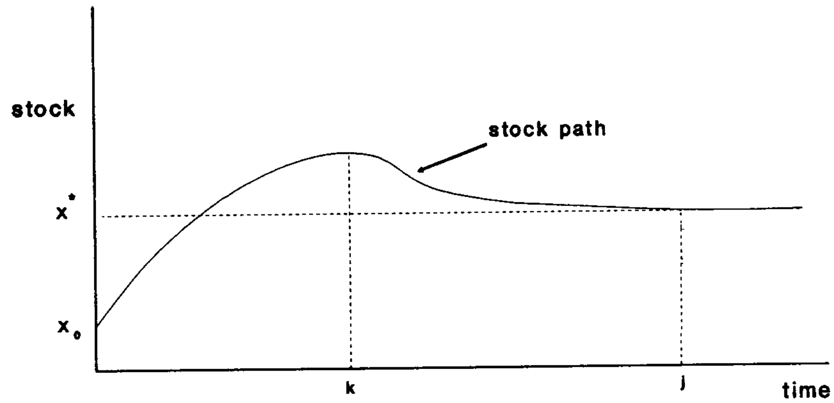

FIGURE 1
THE (NONRATIONAL) CASE WHERE THE GROUNDWATER STOCK RISES ABOVE THE STEADY-STATE

(derived above) that the groundwater stock does not rise above x^*. Appendix A shows that the last possibility implies $\ddot{x}(k) \geq 0$. But $\dot{x}(k) = 0$, $\ddot{x}(k) > 0$ also violates the result that the groundwater stock does not rise above x^*, and $\dot{x}(k) = 0$, $\ddot{x}(k) = 0$ violates the result [13] that the price of groundwater stock shares rises at the rate of interest.[6]

Finally, consider the possibility that the firm chooses to "overpump" groundwater, in the sense that it continues to pump groundwater according to the myopic pumping rule until time T, and then converts to dryland farming. Certainly this behavior is feasible, and at first glance it may seem reasonable; but it is not optimal. Myopic behavior is not in the best interest of the firm. As shown in [11], before time T the price of groundwater stock shares must equal the marginal value of groundwater in consumption. Moreover, at the observed price $p(T)$, *each* of the identical firms is indifferent between buying and selling groundwater stock shares, and so the rational response by the firm is to purchase groundwater stock shares at the observed price to continue groundwater pumping. A firm's groundwater pumping *would* drop to zero in response to a jump in the price of groundwater stock shares, but this too is ruled out by the rationality of firms, insofar as it creates the opportunity for speculative gains. The upshot is that firms do not "overpump" groundwater. The price of stock shares at time $t < T$ reflects the price of stock shares at time T and induces firms to reduce groundwater pumping to let the groundwater stock rise. If firms pump "too much" groundwater at time $t < T$ (that is, the price of groundwater stock shares is too low), each firm has an incentive to reduce its groundwater pumping to reap the speculative gains from the ensuing price jump at time T.

Typical paths for the groundwater stock are shown in Figure 2. In the figure, x^{cp} denotes the common property steady-state stock. The path denoted $x'(t)$ shows the case where the initial state of the groundwater stock is the common property steady-state. The groundwater stock would never fall below this level (such would require a negative price of stock shares), so in light of the results presented above, we know it must rise monotonically over the

[6]Given $\ddot{x}(k) = 0$, we know from [1] that $\dot{u}(k) = 0$. Substituting [8a] into [7a] and differentiating yields

$$g_{uu}\dot{u} + g_{ux}\dot{x} = \dot{p}, \quad t = k.$$

Then with $\dot{x}(k) = \dot{u}(k) = 0$, this result implies $\dot{p}(k) = 0$. But this contradicts result [13].

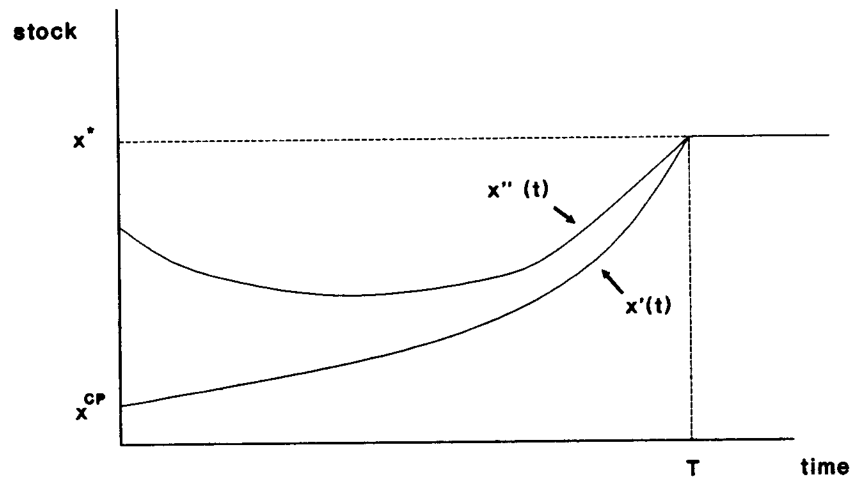

FIGURE 2

TYPICAL PATHS OF THE GROUNDWATER STOCK UNDER THE PRIVATE PROPERTY RIGHTS REGIME

interval (0, T), reaching x^* at T. The path denoted $x''(t)$ shows the case where the initial state of the groundwater resource is higher than the common property steady-state. Due to the initially low price of groundwater stock shares, the stock falls toward the common property steady-state level, ultimately rebounding as the price rises, and reaching x^* at time T.

The Regulator's Problem

The solution of the firm's problem yields the equilibrium pumping rule, $u^{\varepsilon}(x(0), t, T)$. The objective of the regulator is to choose T to maximize the value of the groundwater resource:

$$\max_{T} \int_0^{\infty} e^{-it} Mg(x(t), u^{\varepsilon}(x(0), t, T))\, dt \quad \text{s.t. [1]}, \quad x(0) = x_0. \quad [15]$$

This is the problem addressed in the programming model of the following section. Before proceeding, however, it is worthwhile to examine the issue of the *time inconsistency* in the regulator's problem. This is the conundrum faced by regulators whose optimal policy depends on the initial state of nature. In the problem above, the optimal choice of the control T depends on the initial stock of groundwater, x_0. A change in the stock of groundwater implies a new optimal choice of T. An efficiency-minded groundwater manager might be tempted to continually re-solve [15] for the control T as the groundwater stock changes, in which case the firm-level constraint on groundwater pumping implied by this control (constraint [4]) would itself evolve over time. This continual adjustment by the regulator would be a mistake, however, for two reasons. First, it would contradict one of the goals of the private property rights regime, which is to provide firms with the flexibility to manage their water supplies. And second, firms would learn to anticipate this adjustment process, ultimately causing the regime to fail. To see this, suppose $x(0)$ equals the common property steady-state stock level, x^{cp}. An equilibrium strategy of rational firms aware that the regulator continually re-solves [15] would be to *ignore* the constraint implied by the control T and instead pump groundwater at the myopic rate. In this case the control T would continually recede on the horizon, because at each point in time the initial state of nature used by the regulator to update the control T would remain x^{cp}. This quandary reflects the *time inconsis-*

tency of policy instruments (Kydland and Prescott 1977). In the context of the problem addressed here, the time inconsistency problem is circumvented by establishing rules preventing the regulator from solving [15] more than once.

III. RESULTS FROM A DYNAMIC PROGRAMMING MODEL

Madera County lies in the San Joaquin Valley; it is bounded on the west and south by the San Joaquin River, and on the north by the Chowchilla River. Over 500,000 acres of the county are in irrigated agriculture. Principal crops include almonds, alfalfa, cotton, corn, and grapes. Virtually all agricultural production in the county occurs on land underlain by groundwater. For the purpose of groundwater management, the California Department of Water Resources (DWR 1982) identified three groundwater basins in the county. In this study these basins are referred to as the central, east, and west basins.[7] In the programming model they represent the individual cells of a three-cell aquifer. The programming model includes five essential features, each of which is discussed in turn below.[8]

The probability distribution of surface water supplies to the study area. The largest delivery of water to the study area is the Central Valley Project (CVP) delivery to the central basin, which provides an average annual headgate (farm-level) delivery of 180,000 acre-feet (AF). In the programming model, this delivery is assumed to follow a stationary, gamma-distributed process; all other sources of surface water are fixed at their annual means. Time-series data to derive maximum-likelihood estimates of the distribution of CVP water to the central basin were obtained from the Bureau of Reclamation (USDI 1988).

Functions expressing the net benefit of water consumption. Parametric programming was used to derive polynomial approximations of annual net benefit functions, $h_i(w_{it})$, where h_i is the net benefit of water consumption in basin i, and w_{it} is the water applied in irrigation in basin i in year t. Ultimately the curvatures of the net benefit functions reflect the opportunity for firms to respond to water scarcity by altering the mix of crops produced, by changing the intensity of irrigation management, and by retiring marginal land. So, for instance, in the programming model a reduction in the availability of water in the central basin from 500,000 acre-feet per year to 100,000 acre-feet results in (a) a change in the cropping pattern from a mix of grapes, almonds, irrigated wheat, and cotton to dry wheat only; (b) a change in irrigation management from low intensity methods (e.g., furrow irrigation) to high intensity methods (e.g., drip irrigation); and (c) a decrease in the amount of land under irrigation, from approximately 150,000 acres to less than 40,000 acres, including the complete retirement of all land with class III and class IV soils (the relatively marginal land in the study area).

Functions expressing the cost of groundwater pumping. In the programming model, pumping costs take the form,

$$(\psi_i + \Theta_i D_{it}) u_{it},$$

where ψ_i is the cost of the pumping technology in basin i (the amortized fixed costs per unit water, under assumed intensity of use), Θ_i is the energy cost of lifting one acre foot of water one foot in basin i, D_{it} is the pumping depth in basin i in year t, and u_{it} is the groundwater pumped from basin i in year t. Values of the parameters ψ_i and Θ_i were obtained from the DWR (1982) and updated to 1989 dollars.

Functions expressing return flows and natural inflows to the basins of the study area. Not all water available for irrigation is transpired by the crop. One would expect that as water becomes increasingly scarce, cropping activities become increasingly wa-

[7] The DWR refers to the central, east, and west groundwater basins as Detailed Analysis Units (DAUs) 213, 214, and 215, respectively. The nonurban areas of these basins are approximately 169,000, 176,000, and 157,000 acres, respectively.

[8] A more detailed description of the model is available from the authors.

ter conserving. Among the results of the parametric programming exercise mentioned above were sets of data pairs providing the amount of excess water (water not transpired by the crop) e_i, associated with a chosen level of applied water, w_i. Polynomials were fit to these data to obtain basin-specific excess water functions, $e_i(w_i)$. In the model, all excess water returns to the groundwater aquifer. So, for instance, when 100,000 acre-feet of water is applied in irrigation in the central basin, approximately 19 percent returns to the groundwater aquifer; on the other hand, when 500,000 acre-feet is available for irrigation, the irrigation technology is less water-conserving, and 35 percent of the water returns to the groundwater aquifer. The excess water functions were used along with DWR (1982) estimates of other sources of basin inflow, such as rainfall, seepage from streams and surface water canals, and subterranean water flows, to derive recharge functions reflecting the total periodic recharge in each of the three basins of the study area.

State equations governing the groundwater resource. Three state equations (one for each basin) were derived from the DWR's San Joaquin Hydrologic-Economic Modeling Study (1982). These equations are more sophisticated than the one used in the theoretical discussion (equation [1]), which applied to a model where the aquifer is a single cell. In the programming model, the groundwater resource is treated as a three-cell aquifer—one cell for each of the three groundwater basins of the study area—and annual recharge to the resource is a function of the pumping decisions of firms, as reflected in the recharge functions. Moreover, the state of the groundwater resource in basin i in year $t + 1$ depends not only on the state of nature and pumping activity in basin i in year t, but on other variables as well. For instance, the state of the groundwater resource in the central basin in year $t + 1$ depends on the states of the groundwater resources in the east and west basins in year t, and the amount of groundwater pumped from the west basin in year t. Finally, in the presentation of results from the programming exercise, the state of the groundwater resource is reported as the *height of the water table above sea level.* This reflects the perspective that in California, groundwater scarcity is best cast as a matter of falling water tables (and therefore higher pumping costs), rather than a matter of the physical loss of groundwater stocks. Although casting the groundwater resource in the *stock* dimension simplified the foregoing theoretical analyses, presenting state variable paths in the *depth* dimension is more informative to water managers. Of course, given the one-to-one correspondence between the stock of groundwater and the height of the water table, the currency of the private property rights regime remains the groundwater stock shares held by firms. State equations are reported in Appendix B.

Before examining programming results, a few features of the programming exercise deserve mention. First, the discount rate used in the exercise is 5 percent, and all prices are in 1989 dollars. Second, only the west basin is controlled by the private property rights regime; in the central and east basins, the common property regime persists. The decision to restrict attention to the west basin reflects results from preliminary analyses indicating that due to the hydrologic relationship among the basins of the study area, control of the west basin serves to effectively control the resource of the entire study area. Third, the programming exercise considers the case where initially all three groundwater basins of the study area are at their common property steady-state levels. Finally, the water table in the west basin targeted by the regulator in its reclamation of groundwater stock shares is the *optimal steady-state water table* (OSSWT), measured in feet above sea level.[9]

To reiterate, in the programming exercise the private stock of groundwater held

[9]The OSSWT corresponds to x^* in the theoretical analysis. In the west basin, the OSSWT is 50.2 feet above sea level; by comparison, the land surface in the west basin is 166.6 feet above sea level.

by firms in the west basin is reduced by groundwater withdrawals, and augmented by periodic recharge, in a manner consistent with the state equation governing the water table in the basin. The positive price of stock shares arises because at time T the regulator imposes scarcity by reclaiming sufficient stock shares to restore the groundwater resource to the OSSWT.

Programming Results

To frame the results obtained for the private property rights regime, we consider two polar means of increasing the water table in the west basin from its common property steady-state level to its optimal steady-state level. The first is to allocate the groundwater resource *of the entire study area* via central (optimal) control. The second is to impose upon the west basin the conventional privatization scheme described in the introduction; specifically, the difference in stocks implied by the difference between the common property steady-state water table and the OSSWT is allocated as groundwater stock shares. Because this difference is negative, firms in the west basin must wait for groundwater recharge to raise the water table to the OSSWT (50.2 feet) before they can begin pumping. By definition, under the first method the approach to the OSSWT is optimal, while under the second method the approach is too abrupt and may entail a considerable welfare loss.

In the discussion below, the first method is called the "central control" option. The second method is called the "0-year" option because it is simply a special case of the private property rights regime in which the regulator sets $T = 0$. Figures 3–5 present the expected paths of the water tables in the basins of the study area under each option.[10] In the figures, groundwater tables are initially at their common property steady-state levels. Interestingly, in none of the basins does central (optimal) control increase the water table more than fifteen feet. This raises the question—addressed in a moment—of whether the gain from *any* management of the groundwater resource is significant.

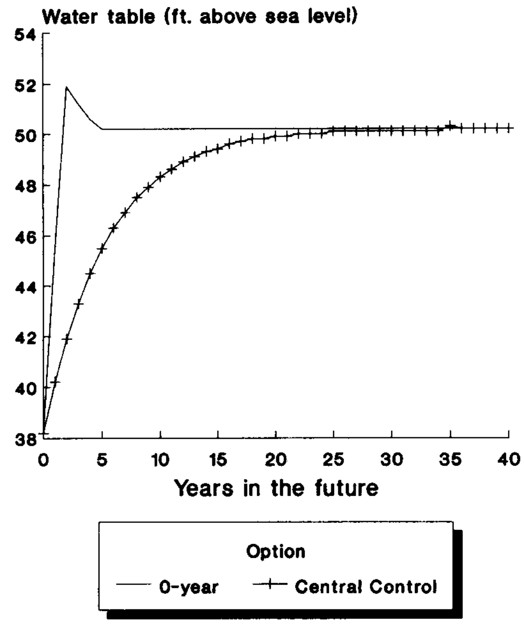

FIGURE 3

COMPARISON OF EXPECTED STATE VARIABLE PATHS IN THE WEST BASIN (MEAN LAND SURFACE IS 166.6 FEET ABOVE SEA LEVEL)

The fluctuations in the expected paths in Figures 3–5 emphasize that the concept of steady-state in a stochastic environment pertains to the long-run *average* state. Due to the recursive nature of the state equations governing the hydrologic relationships among the basins, such fluctuations are not present for the west basin (see Appendix B). Whereas the state of the groundwater resource in the west basin affects the states of the resource in the central and east basins, the state variables in these latter basins—including the only source of uncertainty in the model, the stochastic delivery of CVP water to the central basin—have no effect on the groundwater resource in the west basin. The upshot of this recursive structure is that the state variable path in the west basin is deterministic.

[10]Expected paths were calculated via simulation, using the groundwater pumping policies obtained from dynamic programming.

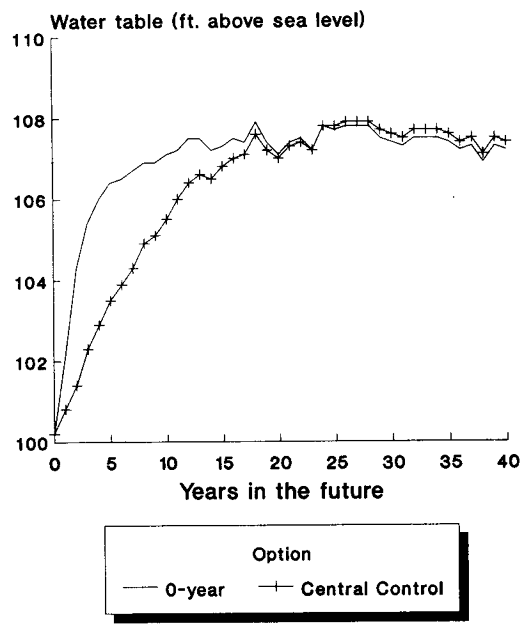

FIGURE 4

Comparison of Expected State Variable Paths in the Central Basin (Mean Land Surface Is 230.9 Feet above Sea Level)

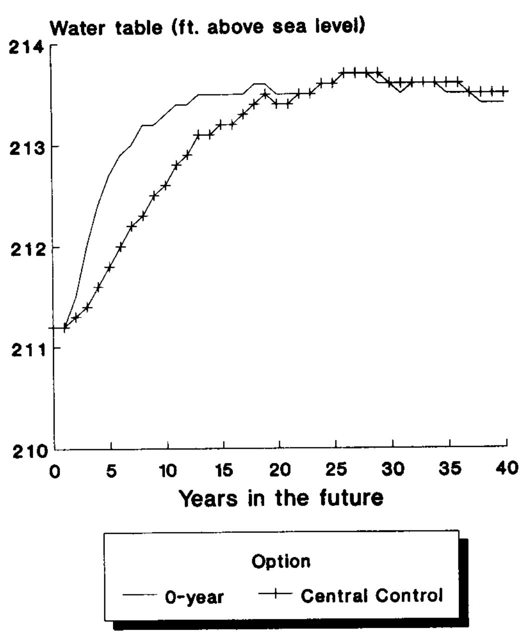

FIGURE 5

Comparison of Expected State Variable Paths in the East Basin (Mean Land Surface Is 326.7 Feet above Sea Level)

Figure 5 shows that the optimal approach to the optimal steady-state in the west basin takes 36 years; the approach under the 0-year option takes only two years, and in fact, initially the state variable path overshoots the steady-state, due to the discrete-time framework of the programming model. Table 1 compares expected values of the groundwater resource under the two options. In the east and central basins the expected value of the groundwater resource is higher under the 0-year option than under the central control option because initially the 0-year option provides greater subsurface flows to these basins by increasing the water table in the west basin more quickly. Nevertheless, by definition the *total* value of the groundwater resource is lower under the 0-year option than under central control; the constraint on groundwater pumping in the west basin that arises under the 0-year option is sufficiently costly to assure this result.

We now turn to the general case of the private property rights regime described above, in which the west basin is privatized and at time $T > 0$ the regulator enforces the OSSWT by reclaiming the appropriate number of groundwater stock shares. Programming results for the private property rights regime are presented in Tables 2–4 and Figure 6. Four distinct variations of the regime are considered, each defined by the value of T. The "5-year option" corresponds to $T = 5$, the "10-year option" corresponds to $T = 10$, and so on. Increasing T reduces the scarcity of groundwater stock shares by postponing the retirement of stock shares by the regulator. Consequently, increasing T serves to increase the rate of groundwater pumping (Table 2) and reduce the rate at which the water table rises (Figure 4). So, for instance, when the water table in the west basin is at 38.2 feet, and the private property rights regime is a year old, the amount of groundwater pumped in the basin ranges from 185,000 acre-feet for $T = 5$ to 255,000 acre-feet for $T = 20$.

Table 3 presents the rational prices of stock shares along the equilibrium state variable path arising under the 5-year option and compares these prices to corre-

TABLE 1

EXPECTED VALUE OF THE GROUNDWATER RESOURCE IMPLIED BY TWO MANAGEMENT OPTIONS, GIVEN WATER TABLES ARE INITIALLY AT THEIR COMMON PROPERTY STEADY-STATE LEVELS (IN MILLIONS OF DOLLARS)

Option	East Basin	Central Basin	West Basin	Total
0-year	229.45	173.00	121.18	523.63
Central Control	229.18	171.98	130.71	531.87

sponding pumping costs. Stock share prices are generally 20–25 percent of the total cost of groundwater pumping. Table 4 presents the expected values of the groundwater resource for the various management options (for the sake of comparison, it includes the results presented in Table 1). The optimal choice of *T* is in the neighborhood of ten years. In fact, a perusal of Table 4 reveals that under the 10-year option, the expected value of the groundwater resource is less than $.4 million lower than under central control.

Table 4 also shows that when the common property regime remains the institutional arrangement governing the allocation of the

TABLE 2

COMPARISON OF THE PUMPING RATES IN THE WEST BASIN IMPLIED BY VARIOUS OPTIONS FOR IMPLEMENTING THE PRIVATE PROPERTY RIGHTS REGIME

		Rate of Groundwater Pumping in the West Basin (1,000 AF)			
		Water Table (Ft. Above Sea Level)			
	Years Since Property Rights Established	38.2	41.6	46.6	50.2
5-year Option:	1	185	202	226	245
	2	161	186	221	244
	3	127	159	205	243
	4	52	84	178	237
	5	0	22	115	214
10-year Option:	1	231	239	250	257
	2	225	235	248	256
	3	217	229	244	254
	4	209	222	239	250
	5	200	214	233	245
	10	0	22	115	214
15-year Option:	1	246	254	268	280
	2	243	251	265	277
	3	240	248	262	274
	4	237	245	258	270
	5	234	241	254	265
	10	200	214	233	245
	15	0	22	115	214
20-year Option:	1	255	263	279	293
	2	253	262	278	291
	3	252	260	276	289
	4	250	258	274	287
	5	248	256	271	284
	10	230	241	254	265
	15	200	214	233	245
	20	0	22	115	214

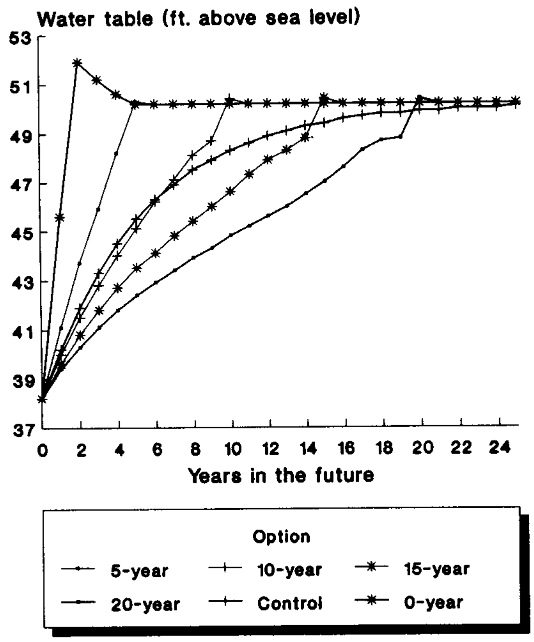

FIGURE 6

COMPARISON OF THE STATE VARIABLE PATHS IN THE WEST BASIN IMPLIED BY VARIOUS MANAGEMENT OPTIONS (MEAN LAND SURFACE IS 166.6 FEET ABOVE SEA LEVEL)

groundwater resource in the study area, the expected value of the groundwater resource is only about $8 million lower than the expected value of the resource under central control. Thus, although the 10-year option of the private property rights regime recovers about 95 percent of the potential grain from resource management (for T = 10), in *absolute* terms this gain is relatively small.

IV. CONCLUSION

When drought conditions in California arise, attention focuses on the state's groundwater resource, which keeps the state's agricultural industry viable—indeed, thriving—during surface water drought. If reactions to the recent drought offer any indication, heavy groundwater pumping and sharply falling groundwater levels will spur demands for comprehensive management of the state's groundwater resource, regardless of whether such management is economically prudent. The private property rights regime examined in this study is a promising and practical alternative to traditional means of groundwater management. The development of such a regime is consistent with the emergence of markets for surface water. Throughout much of the Central Valley, the organizational structure needed to enforce rights to the resource is already in place in the form of irrigation and water districts. This regime is decidedly superior to alternative control approaches when (a) the private information held by firms (such as production possibilities and risk preferences) is difficult for a regulator to obtain and (b) the political climate requires that control of the resource remains in the hands of the extracting firms. The political advantage of the private property rights regime is transparent when one considers this question: given the government asserts its authority to enforce the conservation of groundwater to obtain a particular "sustainable" water table, would a farmer prefer to receive private stock shares equal to, say, the groundwater stock initially beneath his/her land, with the understanding that in the future some shares will be reclaimed by the regulator to reach the desired water table; or would the farmer prefer to be told by the government how much groundwater to conserve in each period?[11]

The point of this paper is that the private property rights regime remains a viable management alternative in the case where groundwater stocks (or water tables) are lower than desired; this situation may already exist in some areas due to the reactive nature of water management. Arguably, the most problematic aspect of the private property rights regime is not its economic inefficiency—in the programming model of Madera County, California this regime recovered 95 percent of the potential gain from management—but rather its time inconsistency. Future work concerning this

[11] Other control possibilities, such as pumping taxes, are even more problematic.

TABLE 3
STOCK SHARE PRICES AND PUMPING COSTS ALONG THE EQUILIBRIUM STATE VARIABLE PATH IN THE WEST BASIN, for $T = 5$

Years Since Property Rights Established	Water Table (Ft. Above Sea Level)	Stock Share Price ($/AF)	Pumping Cost ($/AF)	Total Cost ($/AF)
0	38.2	5.62	22.65	28.27
1	41.1	5.92	22.22	28.14
2	43.7	6.23	21.83	28.06
3	45.9	6.56	21.50	28.06
4	48.2	6.90	21.16	28.06
5	50.3	7.26	20.86	28.12

TABLE 4
EXPECTED VALUE OF THE GROUNDWATER RESOURCE IMPLIED BY VARIOUS MANAGEMENT OPTIONS, GIVEN WATER TABLES ARE INITIALLY AT THEIR COMMON PROPERTY STEADY-STATE LEVELS (IN MILLIONS OF DOLLARS)

Option	East Basin	Central Basin	West Basin	Total
0-year	229.45	173.00	121.18	523.63
5-year	229.23	172.53	128.90	530.66
10-year	229.18	171.99	130.33	531.50
15-year	229.06	171.51	130.90	531.47
20-year	228.94	171.03	131.25	531.22
Central Control	229.18	171.98	130.71	531.87
Common Property	227.79	166.57	129.82	524.18

regime must consider how to operationalize the regime in a manner that firms have no incentive to ignore the rules promulgated by the regulator.

APPENDIX A
EXPLANATION OF WHY THE GROUNDWATER STOCK NEVER DECLINES AFTER AN INITIAL INCREASE

If a change in the direction of the time path of the groundwater stock occurs at time k, then $\dot{x}(k) = 0$.[12] To show that the groundwater stock does not decline after an initial increase, it is sufficient to show that if $\dot{x}(k) = 0$, then $\ddot{x}(k) \geq 0$. The first step is to establish the result

$$g_u(x(k), u(k)) = p(k). \qquad [A1]$$

For $k < T$, this result follows directly from condition [11]. For $k \geq T$, note from [1] that if $\dot{x}(k) = 0$, then $u(k) = r/M$, and so multiplying the first part of [10] by M/r gives

$$\gamma\left(s + \frac{r}{M} + z - s^* - u\right) = 0, \quad t = k. \qquad [A2]$$

Substituting [A2] into [7b] yields

$$g_u - \lambda - \gamma u = 0, \quad t = k. \qquad [A3]$$

Substituting [8b] into [A3] gives the result [A1]. Now differentiate [1] and [A1] to obtain

$$\ddot{x} = -M\dot{u}, \quad t = k, \qquad [A4]$$

$$g_{uu}\dot{u} + g_{ux}\dot{x} = \dot{p}, \quad t = k. \qquad [A5]$$

With $\dot{x} = 0$, we have from [A5],

$$g_{uu}\dot{u} = \dot{p}, \quad t = k. \qquad [A6]$$

[12] A nonsmooth change in direction implies a jump in groundwater consumption (see equation [1]). But this is ruled out by firm rationality.

Rationality assures that the price of groundwater stocks does not fall over time ($\dot{p}$ is nonnegative), and by assumption, $g_{uu} < 0$. Then from [A6], $\dot{u}(k) \leq 0$, and so from [A4], $\ddot{x}(k) \geq 0$.

APPENDIX B
Derivation of Groundwater State Equations

Let x_i, U_i, R_i, and Q_i represent the pumping depth, pumping rate, recharge, and surface water allocation, respectively, in groundwater basin i (the pumping depth is the distance between land surface and the water table). x_i is measured in feet, and U_i, R_i, and Q_i are measured in thousands of acre-feet. Also,

i = 1 indexes the east basin (in the DWR study, this basin is detailed analysis unit [DAU] 214);
i = 2 indexes the central basin (in the DWR study, this basin is DAU 213);
i = 3 indexes the west basin (in the DWR study, this basin is DAU 215);
i = 4 indexes a basin outside the study area (in the DWR study, this basin is DAU 216);
i = 5 indexes a basin outside the study area (in the DWR study, this basin is DAU 234).

The following state equations are obtained from the DWR (1982):

$$x_{1,t+1} = .56803x_{1t} + .15045x_{2t} + .06447x_{5t} + .02539U_{1t} - .02948R_{1t}(U_{1t}, Q_{1t}) + .003458U_{2t} + .008384U_{5t} - .0066195R_{2t}(U_{2t}, Q_{2t}) + .01509R_{5t} + 24.65, \quad [B1]$$

$$x_{2,t+1} = .6549x_{2t} + .21374x_{1t} + .15316x_{3t} + .041328x_{4t} + .02619U_{2t} - .025788R_{2t}(U_{2t}, Q_{2t}) + .007829U_{3t} - .006R_{3t}(U_{3t}, Q_{3t}) + .00216U_{4t} - .025201R_{1t}(U_{1t}, Q_{1t}), \quad [B2]$$

$$x_{3,t+1} = .85584x_{3t} + .0363U_{3t} - .0324R_{3t}(U_{3t}, Q_{3t}) - .34207x_{4t} + .011975U_{4t} - .004898R_{4t} + 52.52. \quad [B3]$$

Based on data supplied by the DWR (1985), reasonable values of x_4, U_4, and R_4 are 125, 653, and 712, respectively; reasonable values of x_5, U_5, and R_5 are 60, 43, and 33, respectively. Substituting these values into the state equations [A1–A3] yields the modified state equations,

$$x_{1,t+1} = .56803x_{1t} + .15045x_{2t} + .02539U_{1t} - .02948R_{1t}(U_{1t}, Q_{1t}) + .003458U_{2t} - .0066195R_{2t}(U_{2t}, Q_{2t}) + 28.38, \quad [B4]$$

$$x_{2,t+1} = .6549x_{2t} + .21374x_{1t} + .15316x_{3t} + .02619U_{2t} - .025788R_{2t}(U_{2t}, Q_{2t}) + .007829U_{3t} - .006R_{3t}(U_{3t}, Q_{3t}) - .025201R_{1t}(U_{1t}, Q_{1t}) + 3.76, \quad [B5]$$

$$x_{3,t+1} = .85584x_{3,t} + .0363U_{3t} - .0324R_{3t}(U_{3t}, Q_{3t}) + 14.09. \quad [B6]$$

In the text, the state of the groundwater resource in basin i is reported as the height of the water table, measured from sea level. This value is obtained by subtracting x_i from the height of the mean land surface for the basin (166.6, 230.9, and 325.7 feet in the west, central, and east basin, respectively).

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