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**A Private Property Rights Regime to Replenish
a Groundwater Aquifer**

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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% of the potential gain from groundwater management.

1.0 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 groundwater stock share is much like any other commodity share; 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 for 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

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, for instance, Kim, Moore, and Hanchar (1989); Nieswiadomy (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 the arrangement as "capacity sharing".

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.

Note, however, that a regulator may circumvent this problem 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 three, 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 four.

II. Theoretical Considerations

To motivate the empirical results of section three, 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 non-negative 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.

³ In this analysis, the groundwater consumed equals the groundwater extracted. In the programming model in section three, this simplification is abandoned.

Following Negri (1989), let, $g_u > 0$, $g_{uu} < 0$, $g_x > 0$, $g_{xx} < 0$, 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,

$$(1) \quad \dot{x}(t) = r - Mu(t),$$

where r is the fixed flow of natural recharge.

Let x^* denote the optimal steady-state stock level. Initially each of the M firms is granted s_0 groundwater stock shares, equal to $1/M^{\text{th}}$ of the groundwater stock available at time 0, x_0 , where, $x_0 < x^*$. Also at time 0, the regulator announces that at time $T > 0$, each firm forfeits s_T^* shares of the groundwater stock, such that, $Ms_T^* = x^*$. The upshot is that for time $t < T$, the aggregate groundwater stock shares held by firms is $x(t)$, and for time $t \geq T$, the aggregate groundwater stock shares held by firms is $x(t) - x^*$. As a practical matter, each firm's stock shares represent its private stock of groundwater. The economic significance of this stock is that it constrains the pumping behavior of the firm; only firms with positive private stocks can pump groundwater. So, for instance, if at time T a firm holds less private stock than s_T^* , it cannot pump groundwater.

2.1 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; in the symmetric case, each firm receives $1/M^{\text{th}}$ of the natural recharge. Formally, we define the tracking variable s , such that for $t < T$, $s(t)$ defines the firm's groundwater stock shares at time t , and for $t \geq T$, the expression, $s(t) - s_T^*$ defines the firm's private stock at time t . This tracking variable evolves over time according to the differential equation,

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

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, for instance, Eswaran and Lewis (1984), Negri (1989), Dixon (1989), and Toman (1986)). So from the firm's perspective, the differential equation (1) can be restated,

$$(3) \quad \dot{x}(t) = r - (M-1)u^e(x(t),t) - u(t),$$

where $u^e(x(t),t)$ is the pumping strategy of all other firms.

The objective of the regulator is to raise the groundwater stock to its optimal steady-state level by eventually restricting the availability of groundwater stock shares. 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 attendant water scarcity by increasing their private reserves of groundwater stock. More will be said about the regulator's problem in a moment; for now it is enough to note that at time $T > 0$ the firm's private stock of groundwater is reduced by the amount announced at time 0, s_T^* , and so the constraint on the firm's groundwater pumping imposed by the private property rights regime changes at time T , as follows:

$$(4a) \quad u(t) \leq s(t) + z(t) + \frac{r}{M}, \quad \geq 0, \quad \forall t < T,$$

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

The constraint (4b) recognizes the possibility that when the regulator reduces the firm's private stock of groundwater at time T by s_T^* , the firm's private stock may be negative for some $t \geq T$, in which case $u(t)=0$. To see this, note that if at time $k \geq T$,

$$s(k) + z(k) + r/M - s_T^* < 0,$$

then (4b) may be stated,

$$(5) \quad u(k) \leq 0.$$

In light of the non-negativity of $u(t)$, the only feasible value of $u(t)$ satisfying (5) is zero.

Formally, the problem of the firm may be stated,

$$(6) \quad \max_{u(t), z(t)} \int_0^{\infty} e^{-it} [g(x(t), u(t)) - p(t)z(t)] dt$$

$$s.t. \quad (2), (3), (4),$$

$$u(t) \geq 0,$$

$$s(0) = s_0, \quad x(0) = x_0,$$

where i is the discount rate, and $p(t)$ is the endogenous price of groundwater stock shares. The solution to this problem satisfies the constraints in (6), and the necessary conditions (applicable at all t),

$$(7) \quad g_u - \lambda - \mu - \gamma \leq 0, \quad u[g_u - \lambda - \mu - \gamma] = 0, \quad u \geq 0;$$

$$(8) \quad p = \lambda + \gamma;$$

$$(9) \quad \dot{\mu} = i\mu - g_x + p_x z - \mu(M-1)u_x^e;$$

$$(10) \quad \dot{\lambda} = i\lambda - \gamma;$$

$$(11) \quad \gamma \left[s + z + \frac{r}{M} - u \right] = 0, \quad t < T, \quad \gamma \left[\max \left(0, s + z + \frac{r}{M} - s_T^* \right) - u \right] = 0, \quad t \geq T.$$

where the arguments of functions are suppressed for the sake of clarity, λ and μ are the current value costate variables for (2) and (3), respectively, and γ is the Lagrangean multiplier on the inequality constraint (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 $\gamma=0$ for $t < T$; 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 is equivalent to setting $\mu=0$. This costate variable is the private marginal user cost arising because groundwater consumption increases the cost to the firm of future groundwater pumping. In a large basin with many users, the assumption $\mu=0$ is a good approximation of reality. Third, the result applicable in the symmetric case, $z(t)=0$, is imposed. In a basin where all firms are identical and stock shares are divided equally among firms, no stock share trading transpires, although the market for stock shares remains viable. And finally, attention is focused on the case where, $u(t)>0, \forall t$. In general there exist cases where the equilibrium solution of the firm's problem includes $u(t)=0$ for some 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. As already mentioned, such a "forced march" to x^* usually has disastrous economic consequences, and so 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 is a reasonable point of departure for deriving analytical results.

In light of these restrictions, relevant necessary conditions for an optimum include (after appropriate substitutions),

$$(7a) \quad g_u = p;$$

$$(8a) \quad p = \lambda + \gamma;$$

$$(10a) \quad \dot{\lambda} = i\lambda - \gamma;$$

$$(11a) \quad \gamma = 0, \quad \forall t < T;$$

$$(11b) \quad u(t) \leq s(t) + \frac{r}{M} - s_T^*, \quad \gamma \geq 0, \quad \gamma \left[s(t) + \frac{r}{M} - s_T^* - u(t) \right] = 0, \quad \forall t \geq T.$$

From (8a), (10a), (11a), and (11b), we know that when the inequality constraint (4) is not binding,

$$(12) \quad \dot{p} = ip.$$

This is the usual result that prices rise at the rate of interest.

After substituting (8a) into (10a), we know that at the steady-state (with $\dot{\gamma}=0$),

$$(13) \quad p = \frac{1+i}{i} \gamma.$$

Now recall that after time T , the aggregate groundwater stock shares held by firms is defined by the expression, $x(t) - x^*$. If at the steady-state, the inequality constraint in (11b) is binding (γ is positive) for one of the identical firms using the groundwater resource, it is binding for *all* firms, and $x(t) = x^*$.⁴ In this light, (13) 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.

To complete this brief characterization of the firm's problem, we wish to determine if there exists a time k such that the inequality constraint on private stocks is not binding, and $\dot{x}(k) = 0$, $\ddot{x}(k) < 0$. By examining this question, we determine whether the groundwater stock ever rises above the steady-state x^* , or more generally, whether the groundwater stock ever falls after an initial increase. Differentiating both sides of (1) and (7a) with respect to t yields,

$$(14) \quad \ddot{x} = -M \dot{u}.$$

$$(15) \quad g_{uu} \dot{u} + g_{ux} \dot{x} = \dot{p}.$$

Substituting (12) into (15), and setting $\dot{x} = 0$, yields,

$$(16) \quad \dot{u} \big|_{\dot{x}=0} = \frac{\dot{p}}{g_{uu}} < 0,$$

and so from (14) we know,

$$(17) \quad \ddot{x}(t) \big|_{\dot{x}=0} > 0,$$

which contradicts the possibility that the groundwater stock declines after an initial increase, though it may increase after an initial decline.

In light of this result, typical paths for the groundwater stock are shown in figure 1. In the figure,

⁴ At the steady-state, $u(t) = r/M$ for each of the identical firms. Substituting this equality into (11b) yields (given the constraint is binding) $s(t) = s_T^*$. Aggregating over all firms gives the result, $x(t) = x^*$.

x^c denotes the common property steady-state stock, and as already noted, x^* denotes the optimal steady-state stock. The path denoted $x'(t)$ shows the case where the initial state of the groundwater stock is the common property (myopic) 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 above we know it must rise monotonically over the 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 towards the common property steady-state level, ultimately rebounding as the price rises, and reaching x^* at time T . In both cases, the price of groundwater stock shares is positive, and so x^* is the steady-state stock level.

The explanation for the result in figure 1 that x^* is reached at time T is fairly straightforward. First, note that by assumption, $u(t) > 0, \forall t$, which eliminates the possibility that x^* is reached after time T .⁵ We also know that x^* will not be reached before time T . This is readily proven 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 (derived above) that the groundwater stock does not decline after an initial increase. From (17) we know that the last possibility ($\dot{x} = 0$) also violates this result, because it also implies that at some point after time k , the groundwater stock must fall to reach the steady-state x^* . So we are left with the conclusion that there exists no $k < T$ such that $x(k) = x^*$.

2.2 The Regulator's Problem

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

⁵ Recall that at time T , the aggregate groundwater stock shares held by firms is $x(T) - x^*$; in the symmetric case, each firm holds $(x(T) - x^*)/M$ stock shares. If x^* is reached after time T (that is, $x(T) < x^*$), firms hold negative stock shares at time T , and by so by design, $u(T) = 0$. But this possibility is ruled out by assumption.

$$\begin{aligned}
 (18) \quad & \max_T \int_0^\infty e^{-it} Mg(x(t), u^e(x(0), t, T)) dt \\
 & \text{s.t. (1),} \\
 & x(0) = x_0.
 \end{aligned}$$

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 (18) 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^* . The equilibrium strategy of rational firms aware that the regulator continually resolves (18) 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^** . This quandary reflects the *time inconsistency* of policy instruments; it is an operational example of the Lucas (1976) critique. Kydland and Prescott (1977) argue that the best way to avoid the time inconsistency of monetary policy in a democracy is to legislate rules which are not effective for at least two years; this averts the type of discretionary (state-dependent) behavior described above. In the context of the problem addressed here, the time inconsistency problem is circumvented by preventing the regulator from solving (18) more than once.

3.0 Results From a Stochastic Dynamic Programming Model of Madera County, California

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. In 1989 total farm revenue in the county exceeded 400 million dollars. 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) identified three groundwater basins in the county (1982). In this study these basins are referred to as the east, central, and west basins.⁶ 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.

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. 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 water districts within the basin.⁷

Functions expressing the net benefit of water consumption. Parametric programming was used to derive polynomial approximations of the annual net benefit functions, $h_i(w_t)$, where h_i is the net benefit in basin i (any of the three basins of the study area), and w_t is the water consumed 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

⁶ The DWR refers to the central, east, and west groundwater basins as Detailed Analysis Units (DAU's) 213, 214, and 215, respectively. The non-urban areas of these basins are approximately 169,000, 176,000, and 157,000 acres, respectively.

⁷ The central basin is composed of the Madera Water District, and the Chowchilla Irrigation District; these districts receive and distribute the water from the CVP.

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 , 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 California Department of Water Resources (DWR 1982).

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 water conserving. Among the results of the parametric programming exercise mentioned above were sets of applied water-excess water data pairs for each basin, (w_i, e_i) , to which polynomials were fit 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% returns to the groundwater aquifer; on the other hand, when 500,000 acre-feet is applied in the basin, the irrigation technology is less water-conserving, and 35% 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. 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 understood to be 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 A.

Before examining programming results, a few features of the programming exercise deserve mention. First, the discount rate used in the exercise is 5%, 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.⁸

To reiterate, in the programming exercise the private stock of groundwater held by each firm in the west basin is reduced by the firm's groundwater withdrawals, and augmented by its share of the periodic recharge, in a manner consistent with the state equation governing the water table in the basin. Firms also augment and reduce their private stocks through their behavior in the market for groundwater stock shares. The positive price of stock shares arises because at time T the regulator reclaims sufficient stock shares to restore the groundwater resource to the OSSWT.

3.1 Programming Results

To frame the results obtained for the private property rights regime, we begin by considering 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

⁸ 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.

shares. Because this difference is negative, firms 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 because firms in the west basin are required to forego productive activities until the OSSWT is reached.

In the discussion below, the first method is denoted the "central control" option, and the second method is denoted 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 2a-c present the expected paths of the water tables in the basins of the study area under both options. 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.

The fluctuations in the expected paths in figures 2a-b emphasize that the concept of steady-state in a stochastic environment pertains to the long run *average* state. Such fluctuations are not present for the west basin, because of the recursive nature of the state equations governing the hydrologic relationships among the basins (see Appendix A). 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 affect 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.

Figure 2c 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 under the 0-year option is *higher* than under the central control option, because initially 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, where the west basin is privatized, and at time $T > 0$ the regulator enforces the OSSWT by forcibly retiring the appropriate number of groundwater stock shares. Programming results for the private property rights regime are presented in tables 2-4, and figure 3. 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 3). 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 a stock shares along the equilibrium state variable path arising under the 5-year option, and compares these prices to corresponding pumping costs. Stock share prices are generally 20-25% of the total cost of groundwater. 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 only \$.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 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 (\$524.2 million vs. \$531.9 million). Thus, although the 10-year option of the private property rights regime recovers about 95% of the potential gain from resource management (for $T = 10$), in *absolute* terms this gain is relatively small.

Conclusion

As drought conditions in California persist, attention continues to focus on the state's groundwater resource, which keeps the state's agricultural industry viable --indeed, thriving-- during surface water drought. If reactions to the 1976-77 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. As surely as this is not the last drought to strike the Central Valley, the days of unregulated groundwater pumping in the Valley are numbered.

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 would be 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. From a political standpoint, a private property rights regime would appear to be decidedly superior to central control, because it grants to the firm the decision about how much water to pump in any given year.

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% of the potential gain from management -- but rather its time inconsistency. Future work concerning this regime must consider how to operationalize the regime in a manner that firms have no incentive to ignore the rules promulgated by the regulator.

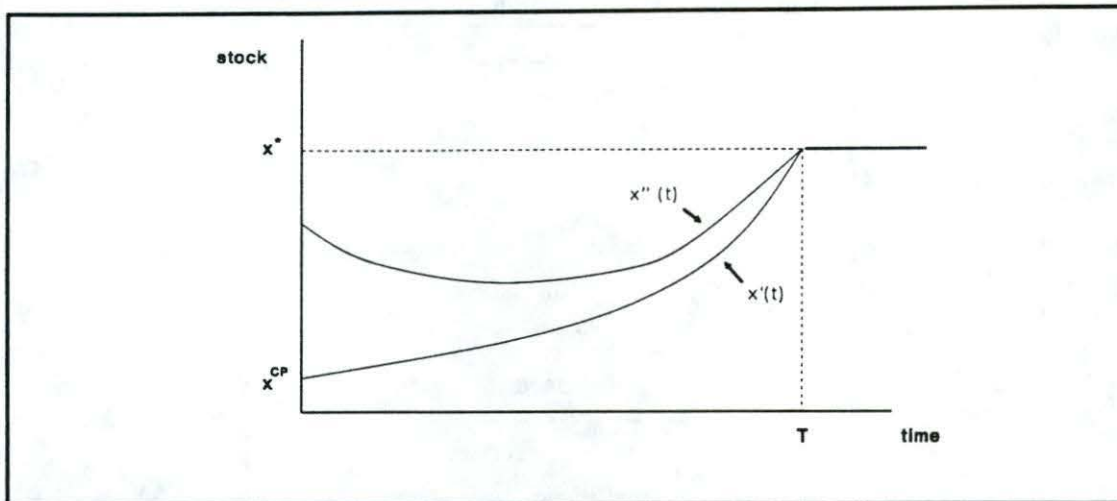


Figure 1. Typical paths of the groundwater stock under the private property rights regime.

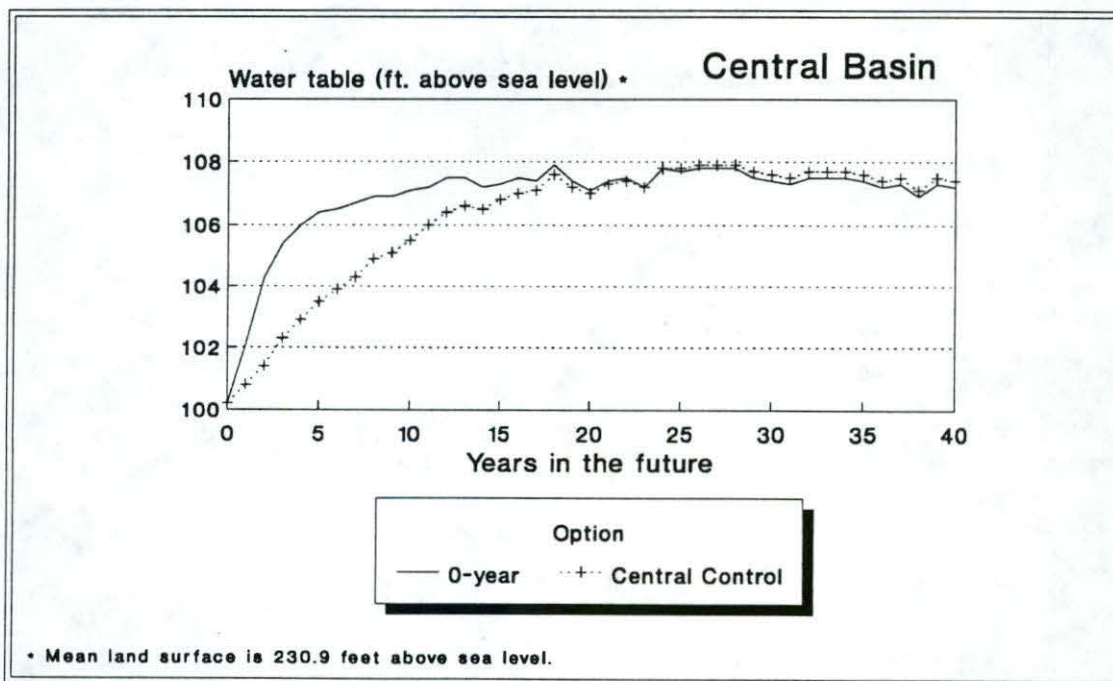


Figure 2a. Comparison of expected state variable paths in the central basin.

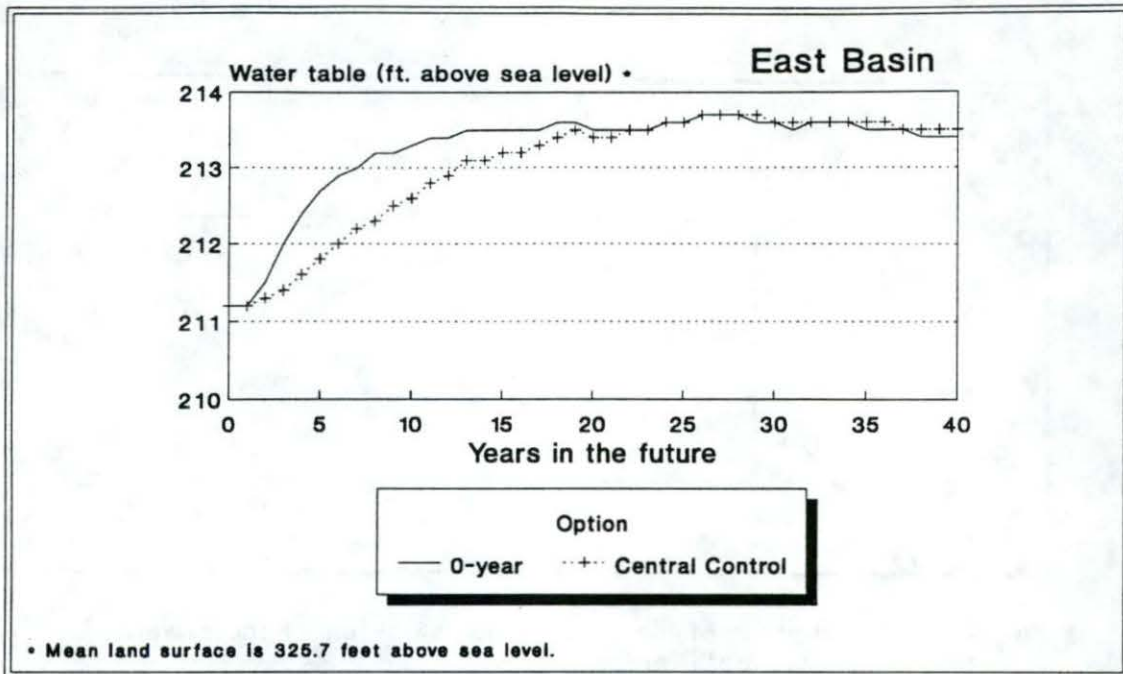


Figure 2b. Comparison of expected state variable paths in the east basin.

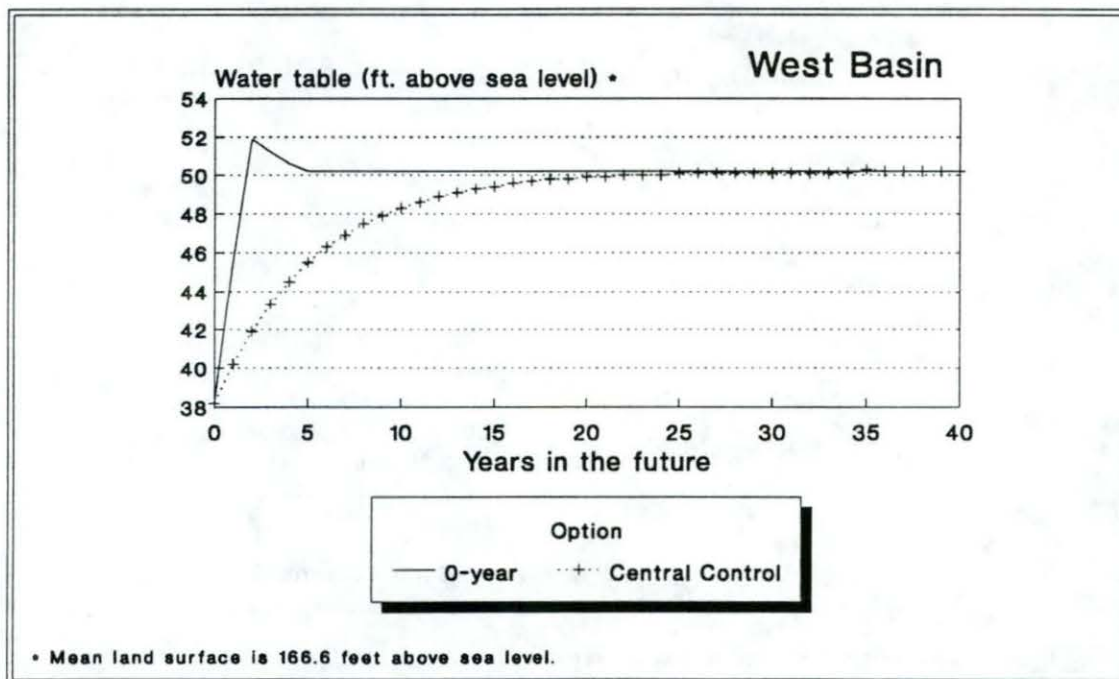


Figure 2c. Comparison of the state variable paths in the west basin.

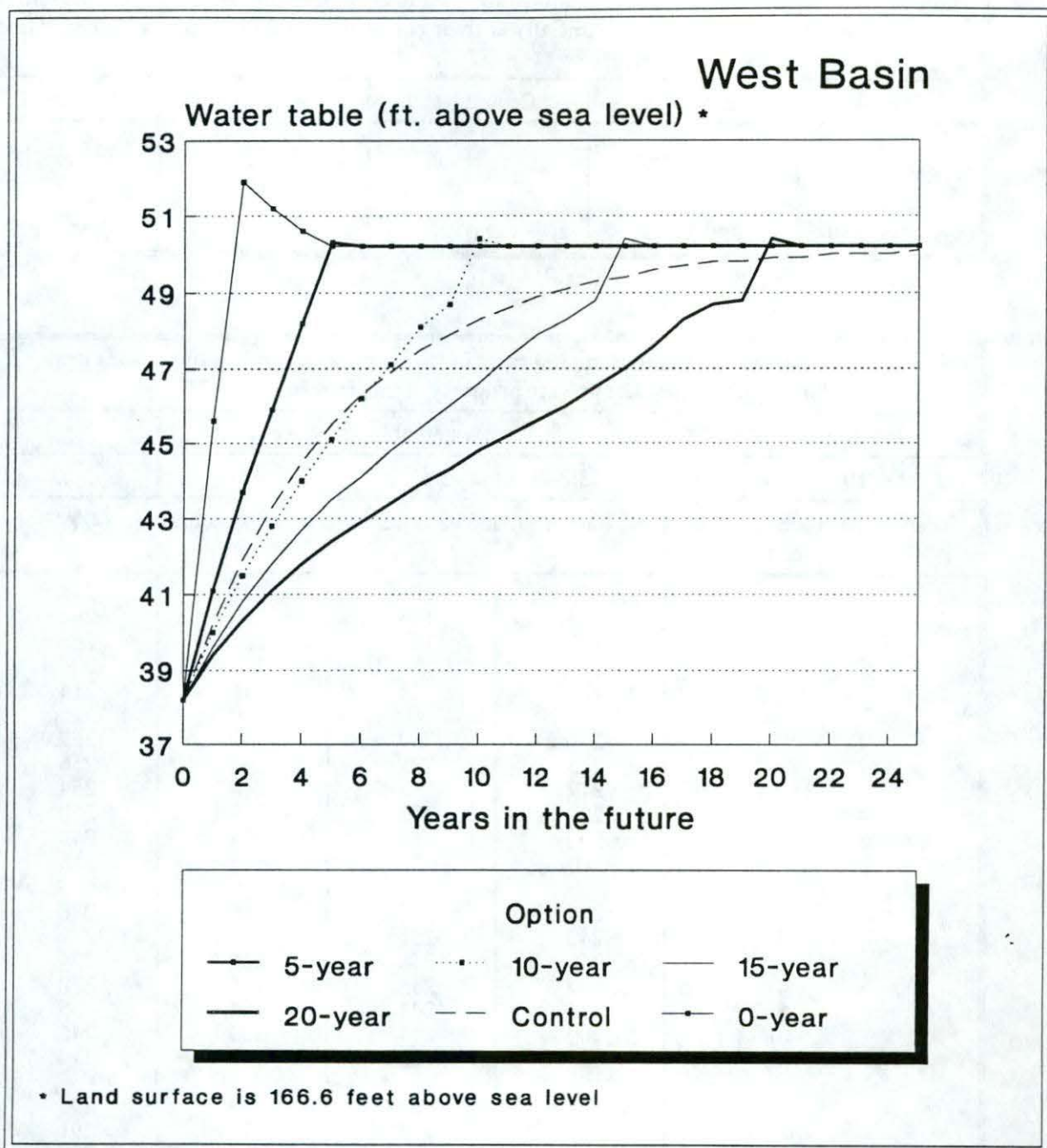


Figure 3. Comparison of the state variable paths in the west basin implied by various management options.

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	229.5	173.0	121.2	523.6
Central control	229.2	172.0	130.7	531.9

Table 2. Comparison of the pumping rates in the west basin implied by various options for implementing the private property rights regime.

Option: value of T				Water table (ft. above sea level)			
5	10	15	20	38.2	41.6	46.6	50.2
Years since property rights established				Rate of groundwater pumping in the west basin (1000 AF)			
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
	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
		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
			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

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	229.5	173.0	121.2	523.6
5-year	229.2	172.5	128.9	530.7
10-year	229.2	172.0	130.3	531.5
15-year	229.1	171.5	130.9	531.5
20-year	228.9	171.0	131.3	531.2
Central Control	229.2	172.0	130.7	531.9
Common Property	227.8	166.6	129.8	524.2

Appendix A: 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):

$$(A1) \quad x_{1,t+1} = .56803x_{1t} + .15045x_{2t} + .06447x_{3t} + .02539U_{1t} - .02948R_{1t}(U_{1t}, Q_{1t}) \\ + .003458U_{2t} + .008384U_{3t} - .0066195R_{2t}(U_{2t}, Q_{2t}) \\ + .01509R_{3t} + 24.65,$$

$$(A2) \quad x_{2,t+1} = .6549x_{2t} + .21374x_{1t} + .15316x_{3t} + .041328x_{4t} + .02619U_{2t} \\ - .025788R_{2t}(U_{2t}, Q_{2t}) + .007829U_{3t} - .006R_{3t}(U_{3t}, Q_{3t}) \\ + .00216U_{4t} - .025201R_{1t}(U_{1t}, Q_{1t}),$$

$$(A3) \quad x_{3,t+1} = .85584x_{3t} + .0363U_{3t} - .0324R_{3t}(U_{3t}, Q_{3t}) \\ - .34207x_{4t} + .011975U_{4t} - .004898R_{4t} + 52.52.$$

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,

$$(A4) \quad x_{1,t+1} = .56803x_{1t} + .15045x_{2t} + .02539U_{1t} - .02948R_{1t}(U_{1t}, Q_{1t}) \\ + .003458U_{2t} - .0066195R_{2t}(U_{2t}, Q_{2t}) + 28.38,$$

$$(A5) \quad x_{2,t+1} = .6549x_{2t} + .21374x_{1t} + .15316x_{3t} + .02619U_{2t} \\ - .025788R_{2t}(U_{2t}, Q_{2t}) + .007829U_{3t} - .006R_{3t}(U_{3t}, Q_{3t}) \\ - .025201R_{1t}(U_{1t}, Q_{1t}) + 3.76,$$

$$(A6) \quad x_{3,t+1} = .85584x_{3,t} + .0363U_{3,t} - .0324R_{3,t}(U_{3,t}, Q_{3,t}) + 14.09,$$

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 basins, respectively).

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