Privatization of Water-Resource Development

By: Stephen P. Holland

"Privatization of Water-Resource Development," *Environmental and Resource Economics* (2006) 34(2): 291-315.

Abstract:
This paper analyzes the inefficiencies from market power and return-flow externalities in private construction of a water project. The model pays special attention to increasing groundwater pumping costs, project set-up costs, limited project capacity, and return flow to the aquifer. For a given capacity, the return-flow externality causes project owners to construct the project too late when the price of groundwater is too high because the external benefit of return-flow to the aquifer is not captured. Market power exacerbates these effects since the project owner delays construction to accelerate groundwater overdraft. The return-flow externality and market power also decrease installed capacity and increase over-draft from the aquifer. Applying the model to the construction of the Central Arizona Project (CAP) for a given capacity, the estimated deadweight loss from hypothetical private construction of the project ($0.853 billion) is substantially less than the literature's estimate of deadweight loss from actual construction by the Bureau of Reclamation ($2.603 billion). However, under the federal subsidies and insecure property rights that accompanied the CAP, private construction results in a larger estimated efficiency loss ($6.126 billion).
Key words: Central Arizona Project, groundwater, optimal control, privatization, return flow, surface water, water, water project construction
JEL classifications: H0, L9, Q2, Q3

Article:
1. Introduction
In the United States, the current trend from public to private control of productive resources has included dramatic deregulation and restructuring in the communications, transportation, and energy industries.[1] However, there remain industries, such as water-resource development, that are still characterized by a high degree of public-sector involvement and might seem ripe for restructuring.[2] Water utilities have been privatized in many countries with some success,[3] and powerful arguments have been made for further privatization of water supply.[4]

Privatization and restructuring increase the need for concern about market failures. For example, problems stemming from market power in the electricity industry increased dramatically when prices were set by deregulated markets rather than by regulators.[5] Similarly, market power is an important consideration when designing tradeable emissions permits to allocate rights to pollute. [6] In water marketing, external harm to third parties is a concern in any transaction of water rights. [7] In each of these examples, policy decisions about market institutions must weigh the inefficiencies from market failure against the inefficiencies of public-sector control.

Historically, the U.S. Bureau of Reclamation has constructed a large percentage of the water projects in the United States, [8] while project construction abroad has often included significant involvement from governmental and non-governmental organizations.[9] Although rare now, private project construction has occurred without explicit public support. [10] Whether public or private, project construction is often controversial both for environmental reasons and for distributional concerns that arise with private ownership of water supplies.[11] This paper addresses two additional concerns from private ownership of water projects: market power and supply externalities. [12]

With private ownership of a water project, market power might be exercised in several ways. First, the owner might have an incentive to reduce deliveries from the project in order to increase the price of water in the destination market. The owner also might not construct the project at the efficient time – given the relative availability of groundwater as a substitute for project water – or might not construct the efficient delivery capacity in a water project.

A private owner also may not realize all the external benefits of the water delivered by the project. In particular, project deliveries may benefit groundwater pumpers by return flow to the aquifer. [13] By increasing the available stock of groundwater, return flow can reduce groundwater pumping costs and reduce potential losses from land subsidence. [14] If these external benefits to the groundwater appropriators – called the return-flow externality – are not internalized by the water project owner, private incentives might not lead the project owner to construct and operate the project efficiently.

While the potential inefficiencies from market power and the return-flow externality are inherent in private water-project development, it is not clear whether a superior alternative exists. One alternative remains: the construction and operation of the project by the public sector. However, public construction of water projects often results in costs being borne by the general public while benefits accrue to certain individuals.[15] This has led to inefficiencies in project construction and water allocation. Holland and Moore (2003) estimated a deadweight loss of over $2 billion from inefficient construction of the Central Arizona Project by the Bureau of Reclamation. [16] Here I estimate the inefficiencies of private construction of a water project and compare them with the earlier estimates of the inefficiencies of public construction.

To analyze the incentives of a private project owner, a model of a water-project construction is developed. The model pays special attention to set-up costs of constructing the project, limited delivery capacity of the project, return flow to the aquifer, and increasing pumping costs of groundwater. Solving the model for the price-taking competitive equilibrium (and com-paring it to the efficient allocation) isolates the inefficiency of the return-flow externality. A dynamic monopoly/competitive-fringe model analyzes the effects of market power.

The model does not explicitly analyze the uncertainty inherent in water-resource development. The exceptionally long planning horizon for water projects requires estimates of water demand, flows of project water, and available stocks of groundwater in the distant future. Such estimates are without a doubt highly imprecise. By not explicitly modeling these sources of uncertainty, the analysis is greatly simplified, but the model results are not clearly biased by this simplification. [17] In particular, I assume that neither the private nor public sector has an inherent advantage in managing these risks. [18]

The paper proceeds in section 2 by presenting the theoretical model of water-project construction when groundwater with increasing pumping costs is available as a substitute. Section 3 calculates the efficient construction timing and allocation of water. Section 4 models the competitive interaction between the private owner of the water project and the groundwater pumpers and derives the incentives of the project owner for construction timing and capacity choice. Section 5 applies the model to the hypothetical construction of the Central Arizona Project by a private firm and compares the estimates of deadweight loss to those of Holland and Moore for the actual construction by the Bureau of Reclamation. Section 6 discusses policy implications and concludes.

2. A Model of Water-Resource Development

Analysis of the inefficiencies of private construction of water projects requires a model of efficient water project construction and an understanding of how private incentives might lead to inefficiencies.

Assume demand for water is downward sloping and invariant over time. [19] Let the benefit from water use be given by $U(Q(t))$, where $Q(t)$ is total water used at time t. [20] Water supply comes from groundwater and imported project water. [21] Water can be imported only after construction of a project. Let $\bar{I}$ represent the limited delivery capacity of the project, and I the quantity of water imported by the project. Water can be imported at constant marginal cost c_I. The set-up costs of constructing the project, $F(\bar{I})$, are convex in delivery capacity, i.e., $F' > 0$, $F'' \geq 0$, and $F(0) = 0$.

For simplicity, let the (exhaustible) groundwater be modeled as a single-cell aquifer. Assume groundwater is replenished to the aquifer by R units of exogenous recharge from precipitation and stream flow and by return flow from the water used at a rate $0 < \alpha < 1$. Thus, total recharge to the aquifer is $R + \alpha Q(t)$. Let $q(t)$ be the quantity of groundwater pumped at t, and let the state variable $S(t) = \int_0^t q(\tau) — R — \alpha Q(\tau) d\tau$ be the cumulative overdraft from the groundwater stock.[22] Since the pumping cost at time t depends on the height that groundwater must be pumped, the pumping cost is an increasing function of cumulative overdraft. Let $c(S(t)) \cdot q(t)$ be the cost of pumping $q(t)$ units of groundwater, where $c' > 0$. Thus pumping costs increase as the groundwater stock depletes.

3. Efficient Water Use

Efficient groundwater mining and project timing can be found by solving the social planner's problem. The planner chooses water usage, the time to build the water project, T, and project deliveries to maximize the present value of consumer surplus less costs, where r is the discount rate. The planner's problem is

$$\max_{q(t),T,I,\bar{I}} \int_0^T e^{-rt}[U(Q) - c(S)q]dt - e^{-rT}F(\bar{I}) + \int_T^\infty e^{-rt}[U(Q) - c(S)q - c_I I]dt \qquad (1)$$

where water usage is $Q(t)=q(t)$ for $t < T$ (i.e., before the project is built) and $Q(t)=q(t)+I$ for $t > T$. Optimization is subject to the constraint on project capacity, $I \leq \bar{I}$; the initial condition, $S(0) = 0$; and the equation of motion of the state variable, $S(t) = q(t) — R — \alpha Q(t)$. The first integral in the planner's objective is discounted net surplus before the project has been built. The second term in the objective is the present value of the set-up costs for the project. The final integral is net surplus after the project has been built and water importation has begun. In the steady state, groundwater mining will cease, i.e., $\dot{S} = 0$. If it is efficient to build the project, steady-state water usage is given implicitly by $Q^{ss} = I^{ss} + R + \alpha Q^{ss}$.

The water usage and extraction paths are found from the first-order conditions of the planner's optimization problem. Let — $\lambda(t)$ be the multiplier of cumulative overdraft defined from the current-value Hamiltonian, and let $\mu(t)$ be the multiplier of the capacity constraint. The first-order conditions for optimal groundwater pumping, project deliveries, and capacity can be written:

$$U'(Q(t)) = c(S(t)) + \lambda(t)(1 - \alpha) \qquad (2)$$

$$U'(Q(t)) \leq c_I + \mu(t) - \alpha\lambda(t) \qquad (3)$$

$$F'(\bar{I}) = \int_0^\infty e^{-rt}\mu(t + T)dt \qquad (4)$$

$$\dot{\lambda}(t) - r\lambda(t) = -c'(S(t))q(t) \qquad (5)$$

Since the fraction α returns to the aquifer, $(1 — \alpha)\lambda(t)$ is the scarcity cost of pumping a unit of groundwater. Equation (2) then equates marginal social benefit with marginal social cost. [23] Since $U'(Q(t))$ is determined by Equation (2), Equation (3) indicates that deliveries from the project should be at capacity if $c(S(t)) + \lambda(t) \geq c_I$ and zero otherwise. Equation (4) shows that the optimal capacity is found by integrating the shadow values of capacity, [24] and Equation (5) is the equation of motion for the shadow value. Since the growth rate of the shadow value is $r - c'q / \lambda$, the Hotelling r-percent rule takes into account the effect of pumping today on pumping costs in the future.[25] In the steady state, the current shadow value is constant, i.e., $\dot{\lambda} = 0$. The steady-state scarcity cost of water is then $c'q / r$ which is the marginal increment to the total pumping cost from pumping an additional unit of groundwater capitalized at rate r. Equation (2) implies that cumulative overdraft in the steady state, S^{ss}, is given by

$$U'(Q^{ss}) = c(S^{ss}) + \frac{c'(S^{ss})}{r}(1-\alpha)q^{ss} \qquad (6)$$

where $q^{ss} = R + \alpha Q^{ss}$. That is, the marginal benefit of water usage in the steady state must exceed the marginal cost of pumping groundwater by the increment to the steady-state pumping cost of mining an additional unit of groundwater.

To compute the efficient time to construct the project, first note that the efficient pumping path need not be continuous at T.[26] Define q^- and q^+ as the limits of the pumping path before and after T, i.e., $q^- \equiv \lim_{t\uparrow T} q(t)$ and $q^+ \equiv \lim_{t\downarrow T} q(t)$. The first-order condition for optimal project timing can be written:[27]

$$\begin{aligned} &U(Q(T)) + \alpha\lambda(T)Q(T) - (c(S) + \lambda(T))q^- + rF \\ &\quad = U(Q(T)) + \alpha\lambda(T)Q(T) - (c(S) + \lambda(T))q^+ - c_I I \end{aligned} \qquad (7)$$

Note that the first three terms are the gross benefits from water usage and return flow less pumping and scarcity costs. The right-hand side is also the net benefit but additionally includes the cost of the imported water. Thus, the equation implies that the project should be built when the net benefit from building the project exceeds the net benefit without the project by the interest payment on the set-up cost.

Since $q^- = q^+ + I$, Equation (7) implies $c(S) + \lambda(T) = c_I + \frac{rF(\bar{I})}{\bar{I}}$ which – with Equation (2) – then implies

$$p^*(T) = c_I + \frac{rF(\bar{I})}{\bar{I}} - \alpha\lambda(T) \qquad (8)$$

Define the trigger price as the marginal benefit (price) at which the project is built. Since $p^*(t)$ increases over time, it eventually reaches the trigger price, $p^*(T)$, at which time it is efficient to construct the project. The trigger price shows that the efficient construction time is when the marginal benefit of water usage plus return flow exceeds the marginal importation cost by the per unit interest payment on the set-up cost. [28]

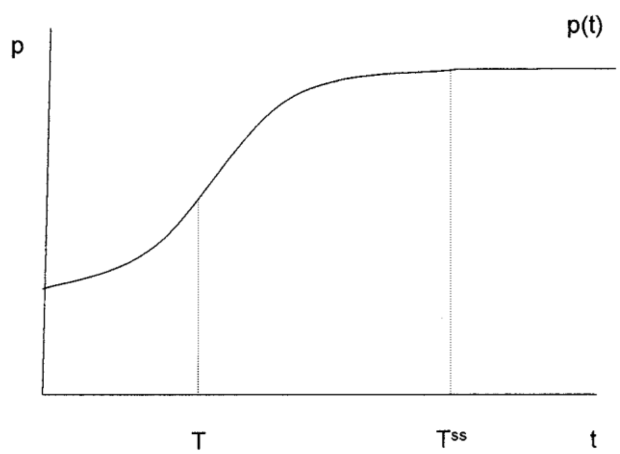

Figure 1. **Marginal benefit (price) path. The project is built when the price reaches the trigger price $p(T)$.**

The solution to the planner's problem is illustrated in Figure 1 with the continuous marginal benefit path $p^*(t) \equiv U'(Q^*(t))$, where $Q^*(t)$ is the efficient water usage. When the steady state is reached at time T^{ss}, the marginal benefit is constant at $p^*(T^{ss}) = U'(Q^{ss})$ and groundwater mining ceases. The water usage and groundwater extraction paths can be found from the marginal valuation (demand) curve. Although $p(t)$ is continuous, groundwater pumping is discontinuous at T. This discontinuous decrease in groundwater pumping is precisely offset by the discontinuous increase in water importation, so water usage does not jump.

4. Private Construction of the Water Project

With market power and externalities, competition may not result in efficient construction and operation of the water project. The competitive interaction between groundwater pumpers and the owner of the water project determines the equilibrium outcome and potential for this inefficiency. The owner of the water project optimizes:

$$\max_{I,\bar{I},T} \int_T^{\infty} \mathrm{e}^{-rt} I[p(t) - c_I]\mathrm{d}t - \mathrm{e}^{-rT}F(\bar{I}), \tag{9}$$

subject to the constraint on project deliveries $I \leq \bar{I}$. Clearly, the important issue is the nature of the competition determining the price path, $p(t)$. The project owner can affect the price path by deciding when to construct the project and how much to import. The groundwater owners affect the price path by their pumping. Since ownership of groundwater is generally dispersed whereas ownership of the water project is concentrated in a single agent, competition is similar to that between a monopoly and a competitive fringe. [29]

Consider several alternate assumptions about price formation. Ground-water owners are assumed either to pump groundwater as private property or as a common pool under free access.[30] This assumption either captures the (lack of) legal protections afforded by groundwater law or captures the effect of physical parameters of the aquifer such as transmissivity.[31] The project owner is either assumed to act as a price taker or to exercise market power. The price-taker assumption isolates analysis of the return-flow externality, whereas the market-power assumption combines both market failures. These assumptions are combined into four scenarios as described in Table I. The subscripts 1–4 denote the values for each of these four scenarios.

First, consider competitive groundwater extraction with well-defined property rights as in Scenarios 1 & 2. Since each of the N pumpers is homogeneous and a price taker, the profit maximization can be written in terms of aggregate quantities as:

$$\max_{q(t)/N} \int_0^{\infty} \mathrm{e}^{-rt} \frac{q(t)}{N} [p(t) - c(S)]\mathrm{d}t, \tag{10}$$

subject to the equation of motion for cumulative overdraft $\dot{S}(t) = q(t) - R - \alpha Q(t)$. The first order conditions $p(t) = c(S) + \lambda(t)(1 - \alpha)$ and $\dot{\lambda}(t) - r\lambda(t) = -c'(S(t))q(t)$ define the price paths which are potential equilibria for the groundwater pumpers.[32] Note that the growth rate of $p(t)$ is

Table I. The scenarios

Project owner	Groundwater rights	
	well-defined	Common-pool
Price taker	1	3
Market power	2	4

identical to the growth rate of the efficient price path contingent on pumping and imports.

Next, consider the price being set by the groundwater extractors pumping from the aquifer as a common pool resource as in Scenarios 3 & 4. When there are many appropriators, the outcome from assuming complete rent (profit) dissipation in every period is a valid approximation to the outcome from analyzing more complicated strategic interactions in a common pool.[33] Complete rent dissipation implies a simple determination of the price path in Scenarios 3 & 4, namely, the price equals the marginal pumping cost in every period, i.e., $p(t) = c(S(t))$.

Having modeled the behavior of the competitive fringe, now turn to the project owner. If the project owner is a price taker, as in Scenarios 1 & 3, then the owner's profit function is as in Equation (9) where $p(t)$ is exogenous, and optimization is with respect to T, I, and $\bar{I}$. Taking the price path as given, the first order conditions for the water project owner are:

$$[p(t) - c_I] - \mu(t) \leq 0 \tag{11}$$

$$I[p(T) - c_I] = rF(\bar{I}) \tag{12}$$

plus Equation (4) from above. Equation (11) implies that imports should be at capacity if price is above marginal cost. Equation (12) indicates that $p(T) > c_I$. This, when combined with Equation (11) and the complementary slackness conditions, implies that project deliveries should be at capacity when the project is constructed. Equation (12) can be re-written as $p(T) = c_I + rF(\bar{I}) / \bar{I}$. This is the trigger price at which the owner would construct the project in Scenarios 1 & 3.

Modeling the project owner as a price taker, as in Scenarios 1 & 3, captures only the return-flow inefficiency. Scenarios 2 & 4 model the potential market power of the project owner. The project owner cannot increase the price in any single period by reducing deliveries since the price in each period is determined by the competitive pumping of groundwater. However, the project owner can cause the groundwater to be depleted more quickly (and thus increase the price more quickly) by delaying construction, restricting deliveries, or installing insufficient capacity.

In Scenarios 2 & 4, the project owner optimizes given that the price depends on cumulative groundwater overdraft and that the growth of cumulative overdraft depends on I. The owner's objective function is still as given in Equation (9) except now the price path is an endogenous function of cumulative overdraft.[34] Let $\gamma(t)$ be the shadow value to the project owner of a marginal increment of cumulative overdraft.[35] Since $q = D(p(t)) — I$, where D is the demand function, the equation of motion can be written $\dot{S}(t) = (1 - \alpha)D(p(t)) - I - R$.[36] The project owner thus chooses I and T to optimize Equation (9) subject to the constraint on project deliveries and the equation of motion. After forming the Hamiltonian, the first order conditions for I, T, and γ can now be written[37]

$$p(t) - c_I - \gamma(t) - \mu(t) \leq 0 \tag{13}$$

$$-I[p(T) - c_I] + rF(\bar{I}) + \gamma(T)I \leq 0 \tag{14}$$

$$\dot{\gamma} - r\gamma = -[I + \gamma(t)(1 - \alpha)D'(p(t))]\frac{\mathrm{d}p(t)}{\mathrm{d}S} \tag{15}$$

Since competitive pumping of groundwater determines the price, the marginal revenue of imports is simply the price in each period. The cost of importing water is the marginal cost, c_I, plus the opportunity cost of an additional unit of cumulative overdraft, γ, plus the capacity cost, μ. Thus Equation (13) equates marginal revenue with the marginal cost of water imports. Note that Equation (13) implies that deliveries are positive only if $p(t) > c_I$. Equation (14) implies that $p(T) — c_I — \gamma(T)$ is positive. Equation (13) then implies that project deliveries are at capacity at T, and the trigger price for Scenarios 2 & 4 is

$$p(T) = c_I + \frac{rF(\bar{I})}{\bar{I}} + \gamma(T) \tag{16}$$

If capacity is exogenously given and *sufficiently limited* such that the project owner never restricts water deliveries below capacity, then the four equilibria are compared in the following proposition. All proofs are in Appendix A.

Proposition 1. *For any sufficiently limited project delivery capacity, i, the trigger prices, construction times, and steady-state overdrafts in the scenarios can be compared as follows:*

$$p^*(T^*) < p_1(T_1) = p_3(T_3) < \min\{p_2(T_2), p_4(T_4)\} \tag{17}$$

$$T^* < T_1 < T_2 \text{ and } T_3 < T_4 \tag{18}$$

$$S^{ss*} = S_1^{ss} = S_2^{ss} < S_3^{ss} = S_4^{ss}. \tag{19}$$

Proposition 1 demonstrates the inefficiency resulting from the return-flow externality and from market power for a given capacity. The trigger prices show that the return-flow externality causes the project to be built at too high a price, i.e., $p^*(T^*) < p_1(T_1) = p_3(T_3)$, and that market power exacerbates this effect, i.e., $p_1(T_1)=p_3(T_3) < \min\{p_2(T_2), p_4(T_4)\}$. The comparison of the construction times illustrates that both market failures lead the project to be built too late for the private-property scenarios, i.e., $T^* < T_1 < T_2$, and that market power leads the project to be built later in the common-pool scenarios, i.e., $T_3 < T_4$.[38] However, Equation (19) shows that the steady-state overdraft is not affected by the return-flow externality nor market power for a given capacity.

Proposition 1 assumes a fixed delivery capacity. However, the project owner has different incentives to install capacity across the scenarios. These incentives can be compared:

Lemma 1. *If $c'' = 0$ and $\dot{\gamma} \geq 0$, then the incentive to build capacity under the four scenarios can be compared for any sufficiently limited delivery capacity $\hat{I}$ as:*

$$\int_0^\infty e^{-rt}\mu^*(T^*+t)dt > \int_0^\infty e^{-rt}\mu_1(T_1+t)dt > \int_0^\infty e^{-rt}\mu_2(T_2+t)dt \tag{20}$$

$$\int_0^\infty e^{-rt}\mu_3(T_3+t)dt > \int_0^\infty e^{-rt}\mu_4(T_4+t)dt. \tag{21}$$

It follows from Lemma 1 that both the return-flow externality and market power decrease the capacity installed by the monopoly. For example, fix $\hat{I}$ at the efficient capacity level. The first inequality in Equation (20) shows that when groundwater is pumped as private property, a price-taking project owner would have less than the efficient incentive to install capacity and, therefore, would build the water project with too little delivery capacity. This inefficiency can be attributed to the return-flow externality. Now fix $\hat{I}$ at the optimal capacity for the price-taking project owner. The second inequality in Equation (20) shows that market power decreases the incentive further, and the monopoly project owner would build even less delivery capacity. Equation (21) shows the analogous result when groundwater is pumped as a common pool.

The proposition and lemma require that capacity be sufficiently limited such that the project owner would never restrict water deliveries below capacity. If the project owner is a price taker, as in Scenarios 1 & 3, Holland (2003) derived a sufficient condition for full capacity utilization and showed the condition is always satisfied with convex set-up costs. The intuition is clear: if capacity is costly to install, the optimizing firm will not install unused capacity.

The question remains whether a monopolist would install capacity that would not be fully utilized. From Equations (13) and (14), capacity would be fully utilized when initially constructed since $\mu(T) > 0$. Setting $\mu(t) = 0$, we can solve for $\tilde{I}(t)$, i.e., the project deliveries that would result if the monopolist were not capacity constrained. Equilibrium project deliveries will then be the smaller of $\bar{I}$ and $\tilde{I}(t)$. The following lemma proves that the latter is always larger.

Lemma 2. *Project deliveries are never below capacity after the project is constructed.*

Lemma 2 shows that project capacities are sufficiently limited in all scenarios. We now have the following proposition:

Proposition 2. *If c¢¢ = 0 and0, the capacities and steady-state overdrafts can be compared as follows:*

$$\bar{I}^* > \bar{I}_1 > \bar{I}_2 \text{ and } \bar{I}_3 > \bar{I}_4 \quad (22)$$

$$S^{ss*} < S_1^{ss} < S_2^{ss} \text{ and } S_3^{ss} < S_4^{ss}. \quad (23)$$

Proposition 2 shows that the return flow externality decreases the capacity installed by the private project owner and that market power decreases capacity further. Moreover, overdraft from the aquifer is greater under private construction due to both the return flow externality and market power.

The proposition assumes (for technical convenience) that the cost of pumping a unit of groundwater, c(S), is linear in cumulative overdraft. This assumption is not critical to the results. The assumption holds if pumping costs are linear in pumping height and specific yield (water per unit volume) of the aquifer is constant, both of which are reasonable assumptions.

Earlier dynamic models of monopolies facing exhaustible competitive fringes have suffered from dynamic inconsistency. 39 The problem arises when a monopolist pledges to overproduce in order to exhaust the fringe's resources more quickly, but then reneges when the resource is exhausted. Since the monopolist always produces at capacity in the models presented here, these models, unlike the earlier literature, do not suffer from dynamic inconsistency.

A question remains about whether the results in Proposition 1 hold with endogenous capacity. If F is linear, Equation (17) clearly holds since average cost and, hence, $rF(\bar{I}) / \bar{I}$ is constant. However, even if F is linear, the proof of Equation (18) is no longer valid. I conjecture, but do not prove, that reasonable conditions could be found under which the results in Proposition 1 hold with endogenous capacity.

5. Private Construction of the Central Arizona Project

To illustrate the magnitude of the dynamic deadweight loss from market power and the return-flow externality, the model is applied to the construction of the Central Arizona Project (CAP) assuming the actual project capacity. CAP imports water from the Colorado River to central Arizona. Fourteen pumping stations lift water 2400 feet to its final destination in Tucson 335 miles from the Colorado River. Deliveries to Tucson began in 1987 after considerable political maneuvering and years of planning and construction by the Bureau of Reclamation. Since property rights to the Colorado River water were poorly defined and the project was heavily subsidized, it is not surprising that the project was constructed too early at considerable loss of efficiency. In fact, Holland and Moore estimate dead-weight loss of $2.6 billion from the inefficient public construction. My model is parameterized below so that the inefficiencies of private construction can be compared directly to Holland and Moore's estimates. [40]

Agricultural demand is assumed to be linear and constant over time with a choke price of $501.26 per acre-foot. [41] Population grows over time, and *per capita* municipal and industrial demand is linear with a choke price of $1793.92. Groundwater pumping costs increase linearly with cumulative overdraft. The cost of lifting one acre-foot of water 100 feet is approximately $18, and the initial pumping height in 1950 is assumed to be 88 feet. Exogenous recharge to the aquifer is assumed to be 126,000 acre-feet per year, and the return-flow coefficient from all water use is approximately 25%.

The hypothetical private owner of CAP must raise the capital to construct the project. Construction costs of CAP are estimated at $5 billion, and annual project deliveries are 1.3 million acre-feet with a delivery cost of $275.32 per acre-foot.42 The public and private interest rates are assumed to be 3.21%. It is also assumed that the firm owns the water in the Colorado River and can sell it to other users before constructing CAP, i.e., that the CAP water has an additional opportunity cost of $37 per acre-foot.

Since capacity is not endogenous in the simulation, a question remains of whether capacity is sufficiently limited such that project deliveries are always at capacity. Equation (A.5) in Appendix A and the analogous equation for Scenario 3, show that the static monopoly price can be used to determine a sufficient condition for full capacity utilization.[43] In particular, if demand at the static monopoly price is greater than capacity, then the monopoly always delivers at capacity. Since a competitive firm delivers more water than a monopoly, it also would always deliver at capacity. Since the static monopoly price is $1034.62 and the steady state price with deliveries at capacity is $1142.87, capacity is sufficiently limited.

The simulated groundwater pumping paths from applying the model to the construction of CAP are illustrated in Figure 2. Pumping increases throughout the first hundred years of the program since population increases faster than scarcity. Thereafter, pumping decreases as groundwater becomes more scarce and population growth slows and stops. When the CAP is constructed in the scenarios between 2073 and 2098, groundwater pumping jumps down to offset CAP deliveries.

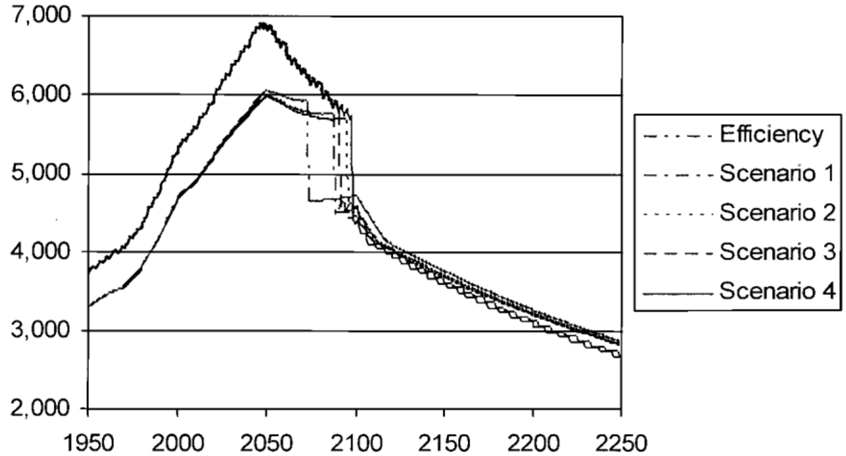

Figure 2. **Annual groundwater pumping in kilo-acre-feet under the five simulation scenarios.**

In Figure 2, all five paths are not clearly distinct. The two common-pool paths (Scenarios 3 & 4) are virtually indistinguishable, and the two private-property paths (Scenarios 1 & 2) and the efficient path are virtually indistinguishable. This occurs since the common-pool paths both pump groundwater until the marginal benefit equals the marginal pumping cost, whereas the private-property and efficient scenarios recognize an additional scarcity cost to pumping groundwater.

Time paths of prices, pumping heights, and water use (not shown) also illustrate the similarity between the private-property scenarios and the efficient scenario in contrast to the common-pool scenarios. Water prices start at about $70 in the private-property and efficient scenarios but increase to $580 after 200 years. However, prices start at about $23 in the common-pool scenarios but increase to $595 after 200 years. Thus prices increase faster in the common-pool scenarios. Pumping heights start at 88 feet in each of the scenarios and after 200 years increase to 2800 feet in the private-property and efficient scenarios and increase to 3300 feet in the common-pool scenarios. Consumption is initially greater in the common-pool scenarios, but then is quite similar in all scenarios after 150 years. Agricultural demand is entirely choked off by 2120 in all the scenarios. The results of the CAP simulation are summarized in Table II. Proposition 1 is illustrated by the construction times, trigger prices and steady-state pumping heights. As shown in Equation (17), the trigger prices are equal in scenarios 1 & 3, but they are higher than the efficient trigger price of $381.19. Since scenarios 1 & 3 isolate the effect of the return-flow externality, these estimated trigger prices illustrate that the externality causes project owners to build the project when the price of water is higher than optimal, i.e., when the trigger price is too high. In scenarios 2 & 4, the trigger prices are still higher. This illustrates that market power causes the project owner to construct the project when the water price is still higher.

Table II. Simulation results for the Central Arizona Project

	Construction year	Trigger price	DWL ($ bill)	Profit ($ mill)	Pumping height (ft)
Efficient*	2073	$381.19	none	$1552.273	6216
Scenario 1	2088	$438.39	$0.009	$1569.365	6216
Scenario 2	2095	$465.54	$0.015	$1570.622	6216
Scenario 3	2091	$438.39	$0.848	$1571.478	6361
Scenario 4	2098	$469.32	$0.862	$1573.039	6361
Common pool*	2062	$293.06	$0.810	$1492.613	6361
Build 1987*	1987	$118.35	$2.612	−$1732.651	6216
Zero Profit	2005	$158.71	$1.118	$40.953	6216
Subsidy ZeroProf	1967	$79.11	$6.126	$22.027	6216

Notes: Scenarios marked by '*' are reported in Holland and Moore.

The construction times illustrate Equation (18) of Proposition 1. The project should have been constructed in 2073, but the return-flow externality causes the project to be built in 2088 or 2091. Modeling market power implies that the estimated construction date is delayed until 2095 or 2098. These estimates illustrate that the return-flow externality causes the project to be built later than optimal and that market power exacerbates the effect.

The steady-state pumping heights in Table II illustrate Equation (19) of Proposition 1. Since water imports from the project are at capacity once it is constructed, there is no deadweight loss from market power or the return-flow externality in the steady state. This is illustrated in Table II by the steady-state pumping heights of 6216 feet across all the private-property scenarios. The pumping height is higher in the common-pool scenarios (6361 feet) but this inefficiency arises from common-pool pumping. The steady-state pumping heights reflect the observation from the groundwater pumping paths that the private-property and efficient scenarios are quite similar to one another but are distinct from the common-pool scenarios.

The observation that scenarios 1 & 2 are quite similar to the efficient scenario is reinforced by the deadweight-loss calculations in Table II. In the private-property scenarios, the deadweight loss from the return-flow externality is $9 million. The addition of market power only increases the deadweight loss to $15 million. In contrast, the deadweight loss in the common-pool scenarios is approximately $850 million. Since the common-pool scenarios have an additional inefficiency, the return-flow externality and market power can be better evaluated by comparing them with the "Common Pool" scenario reported in Table II. This scenario is the second-best outcome reported in Holland and Moore where the project is constructed optimally given that groundwater is pumped as a common pool. This scenario has a deadweight loss of $810 million and is a more relevant baseline for comparing the inefficiencies of scenarios 3 & 4.

Comparison with the relevant baseline allows the relative magnitudes of the inefficiencies from the return-flow externality and market power to be compared. In the private-property scenarios, the return-flow externality leads to $9 million out of a total deadweight loss of $15 million. Thus, 56% of the deadweight loss comes from the return-flow externality whereas 44% comes from market power. Comparing scenarios 3 & 4 to the Common Pool baseline shows that 74% of the additional deadweight loss of $52 million comes from the return-flow externality. This suggests that the two inefficiencies are comparable but that the effect of the return-flow externality is possibly larger.

The deadweight loss of $810 million in the Common Pool scenario in Table II provides another interesting comparison. The combined effects of the return-flow externality and market power imply an estimated deadweight loss of only $15 million in the private-property scenarios and only $52 million additional deadweight loss in the common-pool scenarios. These estimates are small compared to the estimated loss in the

Common Pool scenario of $810 million. This suggests that the inefficiencies from the return-flow externality and market power are smaller than the common-pool inefficiency.

Holland and Moore estimate that the actual construction in 1987 occurred 86 years too early with a deadweight loss of $2.612 billion (Build 1987). This estimate of the inefficiency of public construction is much larger than the estimated losses from private construction under any of the scenarios. This suggests that the incentives facing a private firm may lead to more efficient construction than when construction decisions are made through the public sector. Note also the large negative profit that would have obtained with private construction in 1987 (—$1.7 billion). Although the federal government was willing to bear such large losses, no individual firm would likely bear such losses. This suggests that private construction might avoid the dramatic inefficiencies that have resulted from public construction.

This comparison is not quite appropriate since Holland and Moore analyze public construction under two additional inefficiencies: federal subsidies and insecure property rights to the Colorado River water.[44] These additional inefficiencies can easily be added to the model. With insecure property rights to the river water, a firm would construct the project as soon the present value of the project became non-negative, since waiting longer would risk construction by another firm. [45] With insecure property rights and federal subsidies, the firm would construct the project as soon the present value of the subsidized project became non-negative.

Private construction by a firm with insecure property rights and no subsidies, the “Zero Profit” scenario, is presented in Table II, and shows that the project would have been constructed 68 years too early at a deadweight loss of $1.118 billion. If costs were subsidized as in Holland and Moore’s analysis, estimated construction would have been 106 years too early at a deadweight loss of $6.126 billion as shown in the “Subsidy ZeroProf’’ scenario. Thus, although private construction by itself may not lead to large inefficiencies, it may lead to large deadweight loss in a policy environment of federal subsidies and insecure property rights.

A final interesting point to note in Table II regards the project owner’s profits. The large profit of $1.552 billion in the efficient scenario is rent which accrues to a scarce factor, namely, the dam and project sites. With privatization, this could represent a huge transfer from the project beneficiaries (agricultural, municipal and industrial water users) to the owners of the project. This transfer could be avoided in two ways. First, the project beneficiaries could themselves build the project. This would have the additional benefit of internalizing the return-flow externality. Alternatively, the government could auction the right to construct the project. Thus transfers need not be a barrier to private ownership of a water project, at least in theory.

6. Conclusion

Privatization and restructuring attempt to use the discipline of market forces to improve efficiency of production and allocation. While restructuring has brought remarkable improvements in some industries, it also has increased the potential for market failures. Since public control also can lead to inefficiencies, the decision of whether or not to restructure an industry should rest on whether the benefits of market discipline outweigh the costs of potential market failures.

This paper provides a framework for evaluating market failures in the private construction of a water-importation project. The framework allows analysis of market power and return-flow externalities when the project water is a substitute for exhaustible groundwater. The theoretical analysis shows that, for a given capacity, the return-flow externality leads the project to be constructed later than optimal when the price of groundwater is higher than optimal. This result is obtained because the project owner does not capture the external benefit provided by the project water through return flow to the aquifer. Market power exacerbates these effects by causing the project to be built even later at a still higher price. This occurs since the owner delays project construction to accelerate overdraft from the aquifer and increase the price of water. The return-flow externality and market power also reduce the installed capacity and increase overdraft from the aquifer.

The theoretical model also suggests that the inefficiency of private construction may be small if the optimal capacity is installed and if capacity is small relative to the market. Contingent on optimal capacity, the steady-state overdraft is optimal even if the project is built and operated by a private owner. Thus, there is no inefficiency in the steady state and the only inefficiency arises from the suboptimal construction timing. This suggests that a reasonable policy for reducing deadweight loss might be for a regulator to specify the size of the project (and/or the construction date) and then to allow the private owner to build and operate the project.

Applying the model to the hypothetical construction of the Central Arizona Project by a private firm allows comparison of the relative effects of several inefficiencies for a given capacity. The return-flow externality and market power are estimated to lead to deadweight losses of similar magnitudes ($9 million and $6 million). Since both market failures lead to roughly equivalent efficiency losses, policy makers should devote similar concern to both. However, the inefficiency of market power is likely underestimated here by assuming that the firm installs the optimal capacity.

The estimated deadweight loss in the common-pool scenarios ($810 mil-lion) is larger than the combined estimated effects of market power and the return-flow externality ($15–52 million). This comparison suggests that defining property rights to groundwater or strengthening institutions to manage groundwater pumping is more beneficial than correcting market failures from market power or the return-flow externality again contingent on a given capacity.[46] However, the estimated deadweight loss of the common-pool scenarios likely overstates the loss from poorly defined ground-water rights since the scenarios assume complete spillovers. In other words, the scenarios assume that pumping an additional unit of groundwater reduces the water table equally under all pumpers. In many aquifers, spill-overs are limited by low transmissivity of the aquifer. If aquifer transmissivity is high, these simulations indicate that the benefits of policies improving groundwater management likely exceed the benefits of policies affecting market power and return-flow externalities. [47]

Comparing the estimated deadweight loss from hypothetical private construction with public construction shows larger inefficiencies resulting from public construction. Holland and Moore's estimate of $2.6 billion in deadweight loss from actual construction by the Bureau of Reclamation is larger than the estimated losses from private construction under any of the scenarios (less than $52 million). These estimates suggest that private construction of a water project – although not obtaining the first-best out-come – may not result in large inefficiencies and may avoid some of the worst inefficiencies of public construction. This direct comparison of the inefficiencies of public versus private construction shows that private construction may indeed be preferable.

This direct comparison, however, does not consider the policy environment of federal subsidies and insecure property rights that surrounded the CAP construction. In this policy environment, I estimate that private construction would have led to even larger inefficiencies (estimated at $6.1 billion) even contingent on no capacity distortion. This suggests that privatization of water project construction can result in large inefficiencies if the policy environment is distorted. Thus eliminating subsidies and securing property rights are necessary for private water project construction to result in small inefficiencies.

All these comparisons, however, ignore the effect of market power on the incentive of the project owner to install delivery capacity. If the project owner restricted delivery capacity, the inefficiency from market power could potentially be much larger. In reality, project deliveries are often determined exogenously: e.g., by stream flow or by property rights. In the case of CAP, Arizona's water rights (and hence the project's delivery capacity) were determined by a Supreme Court decision. If the maximum (exogenous) project deliveries are small relative to the market (as with CAP) the monopolist will indeed install sufficient capacity, and the comparisons above are valid.

The inefficiencies from return-flow externalities and market power naturally suggest another possible policy alternative, not analyzed here directly, for ameliorating the inefficiencies of private construction. A common policy recommendation for externalities is to internalize them either through a merger of the affected parties or by creating a market for them. While creating a market for return flow would likely be complicated, merging the affected parties could be quite simple since it only requires that the project beneficiaries acquire the property right to the surface water. If the project beneficiaries make the decisions about construction timing and project deliveries, these decisions will recognize the effect of the return flow on the aquifer and, thus, eliminate the return-flow inefficiency. This ownership structure also has the additional advantage that it eliminates the market power inefficiency since the project owner/beneficiary would no longer have an incentive to restrict deliveries in order to drive up the price. Finally, if the project is owned by the beneficiaries, the question of rent distribution between the owners and beneficiaries is moot. Thus, the inefficiencies of private construction analyzed here could all be eliminated if project beneficiaries construct the project for themselves in a policy environment without subsidies and with a secure property right to the surface water.

Notes

1 . Stanislaw and Yergin (1998) discuss the history of this trend across a variety of countries and industries. The spectacular bankruptcy of Enron and the crisis associated with the restructuring of the California electricity industry may have worked to slow this trend somewhat. However, it is doubtful this trend has been fully reversed.

2. The National Academy of Sciences sponsored a research project entitled "Privatization of Water Services in the United States" to study restructuring of the water industry. See WSTB (2001).

3. Saal and Parker (2001) find price increases outstripped cost increases in privatized water and sewerage companies in Great Britain. Noll et al. (2000) discuss water reforms in six capital cities in developing countries. Bhattacharyya et al. (1994) find evidence that public water utilities are more efficient than private water utilities. See also Bauer (1997), Cowan (1998) and Ogden (1997).

4. For example, see Cowen and Cowen (1998), Spulber and Sabbaghi (1998), Bruggink (1992), Poole and Fixler (1987), Beesley (1997), and Anderson (1983). Lee (1999) discusses future water management issues related to privatization.

5. Joskow and Kahn (2002) and Borenstein et al. (2002) find evidence of substantial market power in the restructured California electricity markets.

6. See Hahn (1984). See Lee et al. (2002) for an alternative view.

7. Anderson (1983) describes a water rights trading scheme based on consumptive use that reduces the potential for external harm.

8. Wahl (1989) reports that 20–25 % of all irrigated land in 17 western states is irrigated by Bureau of Reclamation projects.

9. Currently 1.3% ($1.5 billion) of all World Bank lending is for dam-related costs. World Bank involvement with dams has been declining recently (see World Bank 2002).

10. Wahl (1989) describes how the federal government crowded out private project construction in the Western U.S. in the later part of the 19th century. Ljung et al. (2000) cite the Casecnan in the Philippines as one recent example of a "genuinely privately funded" project.

11. Recent protests have highlighted environmental concerns about the Ebro River Project proposed by the Spanish government. See Albiac-Murillo et al. (2002) for a discussion of policy alternatives to the project.

12. Anderson (1983) and World Bank (1993) discuss market failures in water resource development.

13. Return flow is water which seeps back to the aquifer after the water has been used for some purpose. Return flow is available in the aquifer for appropriators to pump at a future date.

14. Return flow may also have external costs. For example, return flow from irrigation projects might have increased salinity or contain pesticide residue. This would degrade the quality of the water in the aquifer and reduce its value for future uses. Quality issues and land subsidence are not examined in this paper.

15. Lee (1999), Wahl (1989) and Anderson (1983) provide historical overviews of public sector involvement in water resource development in the American west.

16. See also Bain et al. (1966), Eckstein (1958), Hirshleifer et al. (1960), Freeman (1966), and Wahl (1989) for discussions of the inefficiencies of public sector control of water resources. Timmins (2002) estimates the dynamic deadweight loss resulting from municipal water-utility regulators' preferences for low prices.

17. By interpreting the model as analyzing a given state of the world, the results here can be extended to a model with uncertainty if the private and public sectors assign the same probabilities to the states and have the same risk preferences.
18. Expropriation risk might be better managed by the public sector.
19. This invariance assumption is not critical, and demand will be allowed to vary over time in the empirical application.
20. Water "used" refers to gross water usage since recharge to the aquifer from return flow is modeled explicitly.
21. Surface water from local sources will also be important in empirical applications.
22. If groundwater pumping is greater than total recharge, overdraft is positive and groundwater is being "mined." If pumping is less than recharge, then overdraft is negative and the aquifer is being replenished.
23. Alternatively, one can think of $\alpha\lambda(t)$ as the percolation benefit, so that Equation (2) equates the marginal benefits from water use plus percolation with the marginal pumping plus scarcity costs.
24. The analogous result from the peak-load pricing literature is that the capital payment should equal the sum of the shadow values. See also Campbell (1980) and Holland (2003) for similar results in exhaustible resource models.
25. As in the standard Hotelling model, the price grows over time. However its growth rate is lower than the interest rate due to the increasing pumping cost. The growth rate of the price is positive if $\dot{p}(t) = c'(S)[-R = \alpha I] + r\lambda(t)\,(1-\alpha) > 0$. This holds if the increase in the marginal pumping cost is small as cumulative overdraft increases. I assume throughout that $\dot{p}$ is positive.
26. With exogenous set-up costs, the marginal benefit path can jump down, see Hartwick et al. (1986). Holland (2003) shows that with convex set-up costs, firms would not install excessive capacity, and p(t) and Q(t) are continuous.
27. This is equivalent to the condition, $H^- + rF = H^+$, derived by Hartwick et al. (1986).
28. The trigger price can also be written as $p^*(T) = (1 - \alpha)(c_I + rF / I) + \alpha c(S)$, i.e., as a weighted average of import and groundwater costs.
29. In the standard problem of a monopoly and a competitive fringe, the fringe produces at marginal cost and the monopolist maximizes profit based on the residual demand. Here the intertemporal nature of competition makes the problem much more difficult.
30. The common-pool assumption refers to common property under free access and should not be confused with collective ownership and management.
3l. If transmissivity of the aquifer is low, then spillover effects are small, and the aquifer is essentially private property. If transmissivity is high, the aquifer is essentially a common pool.
32. The aggregate shadow value λ is N times the shadow value of each individual aquifer.
33. Brooks et al. (1999) show that the extraction path from assuming rent dissipation, i.e., from assuming zero profit in each period, is the same as the path found by taking the limit of Markov-perfect equilibria as the number of pumpers increases in a common-pool extraction game.
34. The competitive fringe essentially enforces p(t) as a price cap in period t.
35. An increment to cumulative overdraft increases the price of water, so γ is positive.
36. The equation of motion is written differently here to capture the competitive interaction with the groundwater owners. In particular, note that changes in I do not affect current consumption because the competitive groundwater owners are the marginal suppliers.
37. The condition for $\bar{I}$ is in Equation (4).
38. The construction times in the common-pool scenarios cannot be compared theoretically with the efficient construction time because the price path is lower.
39. Seminal papers include Salant (1976), Stiglitz and Dasgupta (1982), Robson (1983), Gilbert (1978), and Lewis and Schmalensee (1982). See Lewis and Schinalensee (1982), Maskin and Newbery (1990) and Newbery (1981) on dynamic inconsistency.
40. See Holland and Moore for further details of the model parameterization.
41. The analysis should not be sensitive to different assumptions about demand elasticity. Since the project always delivers at capacity, demand elasticity only affects the growth rate of γ, (Equation 15).

42. Other delivery capacities are not analyzed due to data limitations. Thus the analysis here does not analyze the owner's incentive to install insufficient capacity.
43. The analogous equation is $(1 - \alpha)\pi'(\hat{p}) = R + r(\hat{p} - c_I) / c'(\hat{S})$
44. California was using some of Arizona's allocation of Colorado River water and tried to establish ownership under the prior appropriation doctrine.
45. This construction date may imply many years of operating losses in order to establish the property right.
46. Policy makers must also consider the cost of correcting the return-flow externality or market power compared with the cost of defining property rights to groundwater or the cost of strengthening institutions.
47. Including costs of land subsidence would likely strengthen this conclusion.

References

Albiac-Murillo, J., J. Tapia-Barcones, A. Meyer and J. Uche, 'Water Demand Alternatives to the Spanish National Plan', Paper presented at the Second World Congress of Environmental and Resource Economists, Monterey, CA, 2002.

Anderson, T. (1983), Water Crisis: Ending the Policy Drought. Washington, D.C.: Cato Institute.

Bain, J. S., R. E. Caves and J. Margolis (1966), Northern California's Water Industry: The Comparative Efficiency of Public Enterprise in Developing a Scarce Natural Resource. Washington, D.C.: Resources for the Future.

Bauer, C. (1997), 'Bringing Water Markets Down to Earth: The Political Economy of Water Rights in Chile, 1976–95', World Development 25, 639–656.

Beesley, M. E. (1997), 'Mergers and Water Regulation', in M. E. Beesley, ed., Privatization, Regulation and Deregulation (pp. 84–92). New York and London: Routledge.

Bhattacharyya, A., E. Parker and K. Raffiee (1994), 'An Examination of the Effect of Ownership on the Relative Efficiency of Public and Private Water Utilities', Land Economics 70, 197–209.

Borenstein, S., J. Bushnell and F. Wolak (2002), 'Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market', American Economic Review 92, 1376–1405.

Brooks, R., J. Controneo, M. Murray and S. Salant (1999), 'When is the Standard Analysis of Common Property Extraction Under Free Access Correct? – A Game-Theoretic Justification for Non Game-Theoretic Analyses', Journal of Political Economy 107, 843– 858. Aug.

Bruggink, T. (1992), 'Privatization versus Groundwater Central Management: Public Policy Choices to Prevent a Water Crisis in the 1990s', American Journal of Economics and Sociology 51, 205–222.

Campbell, H. F. (1980), 'The Effect of Capital Intensity on the Optimal Rate of Extraction of a Mineral Deposit', The Canadian Journal of Economics 13(2), 349–356.

Cowan, S. (1998), 'The Water Industry', in H. Dieter and T. Jenkinson, eds., Competition in Regulated Industries (pp. 160–174). Oxford and New York: Oxford University Press.

Cowen, P. and T. Cowen (1998), 'Deregulated Private Water Supply: A Policy Option for Developing Countries', Cato Journal 18, 21–41.

Eckstein, O. (1958), Water-Resource Development: The Economics of Project Evaluation. Cambridge, MA: Harvard University Press.

Freeman, A. M. III (1966), 'Adjusted Benefit-Cost Ratios for Six Recent Reclamation Projects', Journal of Farm Economics 48, 1002–1012.

Gilbert, R. (1978), 'Dominant Firm Pricing Policy in a Market for an Exhaustible Resource', Bell Journal of Economics 9, 385–395.

Hahn, R. W. (1984), 'Market Power and Transferable Property Rights', Quarterly Journal of Economics 99, 753–765.

Hartwick, J. M., M. C. Kemp and N. V. Long (1986), 'Set-Up Costs and Theory of Exhaustible Resources', Journal of Environmental Economics and Management 13, 212– 224.

Hirshleifer, J., J. C. DeHaven and J. W. Milliman (1960), Water Supply: Economics, Technology, and Policy. Chicago: The University of Chicago Press.

Holland, S. P. (2003), 'Set-up Costs and the Existence of Competitive Equilibria when Extraction Capacity Is Limited', Journal of Environmental Economics and Management 46, 539–555.

Holland, S. P. and M. R. Moore (2003), 'Cadillac Desert Revisited: Property Rights, Public Policy, and Water-Resource Depletion', Journal of Environmental Economics and Management 46, 131–155.
Joskow, P. L. and E. Kahn (2002), 'A Quantitative Analysis of Pricing Behavior in
California's Wholesale Electricity Market During Summer 2000', Energy Journal 23, 1–35. Lee, T. (1999), Water Management in the Twenty-first Century: The Allocation Imperative.
Cheltenham, UK and Northampton, Mass: Elgar.
Lee, J. Hoon, S. Polasky and J. Coggins, 'Marketable Emissions Permits With Large Firms or a Large Market,' mimeo, 2002.
Lewis, T. R. and R. Schmalensee (1982), 'Cartel Deception in Nonrenewable Resource Markets', The Bell Journal of Economics 13, 263–271.
Ljung, P., C. Head and H. Sunman (2000), Trends in the Financing of Water and Energy Resources Projects, Thematic Review III.2 prepared as an input to the World Commission on Dams, Cape Town, http://www.darns.org.
Maskin, E. and D. Newbery (1990), 'Disadvantageous Oil Tariffs and Dynamic Consistency', The American Economic Review 80, 143–156.
Newbery, D. (1981), 'Oil Prices, Cartels, and the Problem of Dynamic Inconsistency', The Economic Journal 91, 617–646.
Noll, R., M. Shirley and S. Cowan (2000), 'Reforming Urban Water Systems in Developing Countries,' in A. Krueger, ed., Economic Policy Reform: The Second Stage. Chicago and London: University of Chicago Press.
Ogden, S. (1997), 'Transforming Frameworks of Accountability: The Case of Water Privatization', in K. Keasey, S. Thompson and M. Wright, eds., Corporate Governance: Economic and Financial Issues. New York: Oxford University Press.
Poole, R. Jr. and P. Fixler Jr. (1987), 'Privatization of Public-Sector Services in Practice: Experience and Potential', Journal of Policy Analysis and Management 6, 612–625.
Robson, A. (1983), 'OPEC Versus the West: A Robust Equilibrium', Journal of Environmental Economics and Management 10, 18–34.
Saal, D. and D. Parker (2001), 'Productivity and Price Performance in the Privatized Water and Sewerage Companies of England and Wales', Journal of Regulatory Economics 20, 61–90. Salant, S. W. (1976), 'Exhaustible Resources and Industrial Structure: A Nash-Cournot
Approach to the World Oil Market', Journal of Political Economy 84, 1079–1093. Spulber, N. and A. Sabbaghi (1998), Economics of Water Resources: From Regulation to Privatization. London and Dordrecht: Kluwer Academic.
Stanislaw, J. and D. Yergin (1998), The Commanding Heights: The Battle Between Government and the Marketplace That Is Remaking the Modern World. New York, NY: Simon and Schuster.
Stiglitz, J. and P. Dasgupta (1982), 'Market Structure and Resource Depletion: A Contribution to the Theory of Intertemporal Monopolistic Competition', Journal of Economic Theory 28, 128–164.
Timmins, C. (2002), 'Measuring the Dynamic Efficiency Costs of Regulators' Preferences: Municipal Water Utilities in the Arid West', Econometrica 70, 603–629.
Wahl, R. W. (1989), Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation. Washington, D.C.: Resources for the Future.
WorldBank, 'Statistics on the World Bank's Dam Portfolio', < http://www.worldbank.org/ html/extdr/pb/dams/factsheet.html > , 2002.
World Bank, 'Water Resources Management', World Bank Policy Paper, 1993.
WSTB, A Newsletter from the Water Science and Technology Board, National Research Council, National Academy of Sciences, Vol. 18 #3, Sept./Oct. 2001.

Appendix A

Proof of Proposition 11. The trigger prices $p_1(T_1) = p_3(T_3) = c_I + \frac{rF(\hat{I})}{\hat{I}}$ are derived from Equation (12). The efficient trigger price, given in Equation (8), is smaller since $-\alpha\lambda(T)$ is negative. Similarly, the trigger prices for assumptions 2 and 4, given in Equation (16), are greater since $\gamma(T)$ is positive.

Since $p^*(T^*) < p_1(T_1)$ there would be excess demand for groundwater in Scenario 1 if the price paths were the same. Therefore the price path must be higher, i.e., $p_1(t) > p^*(t)$. Now if the higher price path were such that T_1 equaled T^*, there would be excess supply of groundwater. Thus $T_1 > T^*$. A similar argument implies that $T_2 > T_1$ since $p_2(T_2) > p_1(T_1)$. Since $p_3(t) = p_4(t)$ for $t \leq T_3$ and $p_3(T_3) < p_4(T_4)$, it follows that $T_3 < T_4$.

The efficient steady state is determined by the three equations $\lambda^{ss*} = \frac{c'(S^{ss*})}{r}[D(p^{ss*}) - \hat{I}]$, $(1-\alpha)D(p^{ss*}) = \hat{I} + R$, and $p^{ss*} = c(S^{ss*}) + (1-\alpha)\lambda^{ss*}$. Since the steady-states in scenarios 1 and 2 are defined by the same equations, it follows that $S^{ss*} = S_1^{ss} = S_2^{ss}$. The steady states for the common-pool scenarios are determined by $(1-\alpha)D(c(S_3^{ss})) = \hat{I} + R = (1-\alpha)D(c(S_4^{ss}))$ so $S_3^{ss} = S_4^{ss}$. The steady state equations then imply that $D(c(S_3^{ss})) = D(p^{ss*}) = D(c(S^{ss*}) + (1-\alpha)\lambda^{ss*})$. Since $\lambda^{ss*} > 0$, $c(S_3^{ss}) > c(S^{ss*})$ and $S_3^{ss} > S^{ss*}$. ■

Proof of Lemma 1. First note that Equations (3), (8), and (11–14) imply that $\mu^*(T^*) = \mu_i(T_i) = \frac{rF(\hat{I})}{\hat{I}}$ for $i = 1, 2, 3, 4$. To compare $\mu^*(T^* + t)$ and $\mu_i(T_i + t)$ for $i = 1, 2$ and for $t > 0$ before the steady state, note that integration by parts implies that $\int_t^\infty e^{-rs}(\dot{\lambda} - r\lambda)ds = -e^{-rt}\lambda(t)$. From Equation (5), it follows that the shadow value of groundwater to the pumpers is

$$\lambda_i(t) = \int_t^\infty e^{-r(s-t)}c'(S_i(s))q_i(s)ds$$

which implies

$$\lambda_i(T_i + t) = \int_t^\infty e^{-r(s-t)}c'(S_i(T_i + s))q_i(T_i + s)ds. \tag{A.1}$$

A similar equation holds for $\lambda^*(T^* + t)$. Since $\dot{p} > 0$ and $p^*(t) < p_1(t) < p_2(t)$, Proposition 1 implies $p^*(T^* + t) < p_1(T^* + t) < p_1(T_1 + t) < p_2(T_1 + t) < p_2(T_2 + t)$ which implies $q^*(T^* + t) > q_1(T_1 + t) > q_2(T_2 + t)$ for all $t > 0$ before the steady state. Since c' is constant by assumption, Equation (A.1) implies $\lambda^*(T^* + t) > \lambda_1(T_1 + t) > \lambda_2(T_2 + t)$. Next note that $\dot{p}_i = c'(S_i)\dot{S} + \dot{\lambda}_i(1-\alpha) = c'(S_i)(q - R - \alpha Q - (1-\alpha)q) + r\lambda_i(1-\alpha) = c'(S_i)(-R - \alpha\hat{I}) + r\lambda_i(1-\alpha)$ with a similar equation for $\dot{p}^*$. Since R and $\hat{I}$ are constants, $\dot{p}$ varies with λ across scenarios which implies $\dot{p}^*(T^* + t) > \dot{p}_1(T_1 + t) > \dot{p}_2(T_2 + t)$. Therefore $\dot{\mu}^*(T^* + t) = \dot{p}^*(T^* + t) + \alpha\dot{\lambda} > \dot{p}^*(T^* + t) > \dot{p}_1(T_1 + t) = \dot{\mu}_1(T_1 + t) > \dot{p}_2(T_2 + t) > \dot{p}_2(T_2 + t) - \dot{\gamma}_2(T_2 + t) = \dot{\mu}_2(T_2 + t)$ where the equalities follow from Equations (3), (11), and (13). Since $\mu^*(T^*) = \mu_1(T_1) = \mu_2(T_2)$, this implies $\mu^*(T^* + t) > \mu_1(T_1 + t) > \mu_2(T_2 + t)$ for all t. The comparison of the integrals in Equation (20) follows directly.

To compare $\mu_3(T_3 + t)$ and $\mu_4(T_4 + t)$ for every $t > 0$ before the steady state, first note that Proposition 1 shows that $p_3(T_3) < p_4(T_4)$ and $T_3 < T_4$. Since $p_3(t) \leq p_4(t)$, it follows that $p_3(T_3 + t) \leq p_4(T_3 + t) < p_4(T_4 + t)$ and $q_3(T_3 + t) > q_4(T_4 + t)$. This implies the inequality $\dot{p}_3(T_3 + t) = c'(S_3(T_3 + t))\dot{S}_3(T_3 + t) = c'(S_3(T_3 + t))[(1-\alpha)q_3(T_3 + t) - r - \alpha I] > c'(S_4(T_4 + t))[1-\alpha)q_4(T_4 + t) - r - \alpha I] = \dot{p}_4(T_4 + t)$ which implies that $\dot{\mu}_3(T_3 + t) = \dot{p}_3(T_3 + t) > \dot{p}_4(T_4 + t) > \dot{p}_4(T_4 + t) - \dot{\gamma}_4(T_4 + t) = \dot{\mu}_4(T_4 + t)$. Since $\mu_3(T_3) = \mu_4(T_4)$, this implies $\mu_3(T_3 + t) > \mu_4(T_4 + t)$ for all $t > 0$. ■

Proof of Lemma 2. For the efficient allocation and Scenarios 1 & 3, the proof is in the text.

In Scenario 2, the price path is given by $p_2(t) = c(S) + \lambda(t)(1-\alpha)$ where the growth rate of λ is given by $\dot{\lambda}(t) - r\lambda(t) = c'(S(t))[D(p_2(t)) - \tilde{I}]$. In equilibrium, $\gamma(t) = p_2(t) - c_I$ so that $\dot{\gamma} = \dot{p} = c'(S)\dot{S} + (1-\alpha)\dot{\lambda} = r[p_2(t) - c(S)] + c'(S)[-\alpha\tilde{I} - R]$. Noting that $\frac{dp_2(t)}{ds} = c'(S)$ and substituting in Equation (15) yields

$$r[p_2(t) - c(S)] + c'(S)[-\alpha\tilde{I} - R] - r[p_2(t) - c_I]$$
$$= -[\tilde{I} + (p_2(t) - c_I)(1-\alpha)D'(p_2(t))]c'(S)$$

which can be solved for $\tilde{I}$:

$$\tilde{I} = -(p_2(t) - c_I)D'(p_2(t)) + \frac{R}{(1-\alpha)} + \frac{r(c(S) - c_I)}{(1-\alpha)c'(S)} \tag{A.2}$$

Note that the first term of the expression for $\tilde{I}$ is $D(p) - \pi'(p)$. Thus, if $p_2(t) = c_I$, the first term would be zero, but if the price were the monopoly price, the first term would be the monopoly demand. Thus, $\tilde{I}$ is clearly increasing. Since $I(t) = \min\{\bar{I}, \tilde{I}(t)\}$ and $I(T) = \bar{I}$, it follows that $I(t) = \bar{I}$ for all t in Scenario 2.

In Scenario 4, the price path is $p_4(t) = c(S)$. As above, if $\mu(t) = 0$, the equilibrium is given by Equations (13) and (15). If $\tilde{I} > 0$, then $\gamma(t) = c(S) - c_I$ and $\dot{\gamma} = c'(S)\dot{S}$. Since $p_4(t) = c(S)$, it follows that $\frac{dp(t)}{dS} = c'(S)$. Equation (15) can now be written:

$$\begin{aligned} &c'(S)[(1-\alpha)D(c(S)) - \tilde{I} - R] - r(c(S) - c_I) \\ &= -c'(S)[\tilde{I} + (c(S) - c_I)(1-\alpha)D'(c(S))] \end{aligned} \tag{A.3}$$

which can be written

$$(1-\alpha)[D(c(S)) + (c(S) - c_I)D'(c(S))] = R + \frac{r(c(S) - c_I)}{c'(S)} \tag{A.4}$$

This equation can be written:

$$(1-\alpha)\pi'(c(S)) = R + \frac{r(c(S) - c_I)}{c'(S)} \tag{A.5}$$

Define $G(S) \equiv (1-\alpha)\, \pi'(c(S))$, i.e., the left side of Equation (A.5) and $H(S) \equiv R + \frac{r(c(S) - c_I)}{c'(S)}$. Under mild conditions $G' < 0$ and $H' > 0$. This implies that there is a unique $\tilde{S}_4$ for which $G(\tilde{S}_4) = H(\tilde{S}_4)$ and Equation (A.5) holds. Therefore, whenever $\tilde{I} > 0$ the cumulative overdraft must be such that Equation (A.5) holds. If this is the case, the state $\tilde{S}_4$ must be the steady state. Thus there would be no deliveries from the water project until the cumulative overdraft reached $(\tilde{S})_4$ and then project deliveries would be $\tilde{I} = (1-\alpha)D(c(\tilde{S}_4)) - R$. Since $\tilde{I}(t)$ is increasing, it follows that $I(t) = \bar{I}$ for all t in Scenario 4. ■

Proof of Proposition 2. The relationships among the capacities is shown in the text following Lemma 1.

The efficient steady state is determined by the three equations $\lambda^{ss*} = \frac{c'(S^{ss*})}{r}[D(p^{ss*}) - \bar{I}^*]$, $(1-\alpha)D(p^{ss*}) = \bar{I}^* + R$, and $p^{ss*} = c(S^{ss*}) + (1-\alpha)\lambda^{ss*}$ and the steady-states in scenarios 1 and 2 are defined by similar equations. The second equation implies that when $\bar{I}$ decreases, p^{ss} increases and $[D(p^{ss}) - \bar{I}^{ss}]$ decreases. The first equation then implies that λ^{ss} decreases since c' is constant by assumption. The third equation then implies that $c(S^{ss})$ and S^{ss} increase.

The steady states for the common-pool scenarios are determined by $(1-\alpha)D(c(S_3^{ss})) = \bar{I}_3 + R > \bar{I}_4 + R = (1-\alpha)D(c(S_4^{ss}))$ so $S_3^{ss} < S_4^{ss}$.