

Privatization of Water-Resource Development

Stephen P. Holland
University of North Carolina Greensboro ^{*†}

July 9, 2004

Abstract

Restructuring of the water industry has occurred in some countries and advocates of reform have called for increased privatization. This paper analyzes the potential inefficiencies from market power and return-flow externalities in private construction of a water project that augments local water supplies with imported surface water. The model of water-project construction pays special attention to exhaustibility of groundwater, increasing groundwater pumping costs, project set-up costs, limited project capacity, and return flow to the aquifer. Groundwater owners are assumed to pump groundwater either from a common pool or as private property. The perfect-competition version of the model shows that the return-flow externality causes project owners to construct the project later than optimal when the price of groundwater is higher than optimal because the external benefit of return-flow to the aquifer is not captured. The dynamic monopoly/competitive-fringe version of the model shows that market power exacerbates these effects since the project owner delays construction to accelerate groundwater exhaustion. The return-flow externality and market power also decrease the incentive of the private owner to install capacity implying that the delivery capacity of the project might be too small. Applying the model to the construction of the Central Arizona Project (CAP) shows that 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 is estimated to result in similarly large efficiency losses (\$6.126 billion).

Keywords: Water, privatization, water project construction, return flow, groundwater, surface water, optimal control, Central Arizona Project.

*Send correspondence to: Stephen P. Holland, Dept. of Economics, University of North Carolina, Greensboro, NC 27402-6165, sphollan@uncg.edu.

†Special thanks to Severin Borenstein, Michael Hanemann, Chad Hogan, Erin Mansur, Michael R. Moore, Stephen Salant, Lucie Schmidt, and Ken Snowden. Thanks also to the University of California Energy Institute and seminar participants at UC Berkeley, UNCG, Amherst College, University of Alberta, Rensselaer Polytechnic, St. Joseph's University, CSU-Sacramento and Clark University.

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.

This paper evaluates market failures in the private construction of a water project that augments local water supplies with imported surface water.⁸ Historically, the U. S. Bureau of

¹Stanislaw and Yergin (1998) discuss the history of this trend across a variety of countries and industries. The spectacular bankruptcy of Enron and the recent 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.

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

³Saal 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).

⁴For 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.

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

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

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

⁸Anderson (1983) and World Bank (1993) discuss market failures in water resource development.

Reclamation has constructed a large percentage of the water projects in the United States,⁹ and project construction abroad has often included significant involvement from governmental and non-governmental organizations.¹⁰ Project construction is often controversial both for environmental reasons¹¹ and for distributional concerns that arise with private ownership of water supplies. This paper addresses two additional concerns from private ownership of water projects: market power and supply externalities.

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 exhaustible groundwater as a substitute for project water—or might not construct the efficient delivery capacity in a water project.

A private owner of a water project also may not realize all the external benefits of the water delivered by the project. In particular, deliveries from a water project may benefit groundwater pumpers by return flow to the aquifer.¹² By increasing the available stock of groundwater, return flow can reduce groundwater pumping costs and reduce potential losses from land subsidence.¹³ 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.

⁹Wahl (1989) reports that 20-25% of all irrigated land in seventeen western states is irrigated by Bureau of Reclamation projects.

¹⁰Currently 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).

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

¹²Return flow is water which seeps back to the aquifer after the water has been used for some purpose. Return flow is stored in the aquifer and is available for appropriators to pump at a future date.

¹³Return 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 are not examined in this paper.

While the potential inefficiencies from market power and the return-flow externality are inherent in private water-project development, it is not clear that a superior alternative exists. One alternative remains 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.¹⁴ This has led to inefficiencies in project construction and water allocation. For example, 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.¹⁵ Here I build a framework to estimate the inefficiencies of private construction of a water project. These estimates can then be compared with the earlier estimates of the inefficiencies of public construction.

To analyze the incentives of a private project owner, a model of 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 exhaustibility of groundwater.¹⁶ Holland (2003) derived sufficient conditions for existence of a competitive equilibrium in an exhaustible resource model with set-up costs if capacity is sufficiently constrained. Solving the model for the price-taking competitive equilibrium isolates the inefficiency of the return-flow externality.¹⁷

The competitive equilibrium does not analyze the effects of market power since it (unrealistically) assumes the water-project owner behaves as a price taker. A more realistic treatment would model the market power of the project owner but would treat the groundwater pumpers as a

¹⁴Lee (1999), Wahl (1989) and Anderson (1983) provide historical overviews of public sector involvement in water resource development in the American west.

¹⁵See also Bain, Caves, and Margolis (1966); Eckstein (1958); Hirshleifer, DeHaven, and Milliman (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.

¹⁶The planner's problem for this model is identical to that presented in Holland and Moore (2003). This allows comparison of the estimates of inefficiencies of private construction with their estimates of the inefficiencies of public construction.

¹⁷The competitive equilibrium need not be efficient due to the return-flow externality.

competitive fringe. Unfortunately, the dynamic monopoly/competitive-fringe model of exhaustible resources, pioneered by Salant (1976), suffers from lack of subgame perfection and from dynamic inconsistency.¹⁸ The model presented here is most similar to a model in Stiglitz and Dasgupta (1982) in which an exhaustible resource is extracted competitively but the backstop technology is patented. Their equilibrium is characterized by a price path that grows at the rate of interest to the monopoly price. This equilibrium requires the monopolist to precommit to produce more than the monopoly quantity after the resource is exhausted. This induces the competitive fringe to exhaust the resource more rapidly at lower prices. However, once the resource is exhausted, the monopolist has an incentive to renege on its precommitment by reducing production, so the equilibrium is not dynamically consistent.

Unlike the earlier work, the common-pool version of the model presented here does not suffer from dynamic inconsistency. When groundwater pumping is from a common pool and there are many appropriators, the outcome from assuming rent (profit) dissipation in every period is a valid approximation to the outcome from analyzing more complicated strategic interactions.¹⁹ With rent dissipation in every period, the pumpers do not pump based on expectations about future prices but rather based solely on current costs. Since expectations about future water imports are irrelevant to the current pumping decision, the equilibrium is dynamically consistent.

The dynamic inconsistency of the private-property model presented here is mitigated for two reasons. First, the limited delivery capacity of the project implies that the monopoly project owner can only precommit to deliver a limited amount of water. If project capacity is less than the monopoly quantity, the monopolist does not want to renege on this precommitment. Second,

¹⁸Additional seminal papers include Lewis and Schmalensee (1980), Stiglitz and Dasgupta (1982), Robson (1983), Gilbert (1978), and Lewis and Schmalensee(1982). See Lewis and Schmalensee (1982), Maskin and Newbery (1990) and Newbery (1981) on dynamic inconsistency.

¹⁹Brooks *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.

increasing pumping costs of groundwater imply that groundwater is not physically exhausted. Thus, if the monopolist were to attempt to renege on its prior commitments by reducing project deliveries, additional groundwater could be pumped to offset any price increase.

One final comment about the model is appropriate. The model does not explicitly analyze the uncertainty inherent in water-resource development. The exceptionally long planning horizon for water projects requires estimates of population and water demand in the distant future. Such estimates are without a doubt highly imprecise. In addition, flows of project water and available stocks of groundwater are also uncertain. By not explicitly modeling these sources of uncertainty, the analysis is greatly simplified, but the model results are not clearly biased by this simplification.

The paper proceeds in Section 2 by presenting the theoretical model of water-project construction when exhaustible groundwater is available as a substitute. Increasing pumping costs, project set-up costs, limited project capacity, and return flow are given special attention in the model. 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. The perfect-competition version of the model isolates the analysis of the return-flow externality, and the monopoly/competitive-fringe version of the model analyzes the combined market failures. Section 5 then compares the steady states for a simple numerical example. Section 6 applies the model to the hypothetical construction of the Central Arizona Project by a private firm. Estimates of the deadweight loss from private construction are then compared to Holland and Moore's estimates of deadweight loss from the actual construction by the Bureau of Reclamation. Section 7 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. The model presented here explicitly accounts for exhaustibility of groundwater, increasing groundwater pumping costs, large set-up costs of project construction, limited project delivery capacity, and return flow to the aquifer from project water.

Assume demand for water is downward sloping and invariant over time.²⁰ Let the benefit from water use be given by $U(Q(t))$ where $Q(t)$ is total water used at time t .²¹ Water supply comes from groundwater and imported project water.²² 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 , and the set-up costs of constructing the project are represented by F .

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 $S(t) \equiv \int_0^t q(\tau) - R - \alpha Q(\tau) d\tau$ be the cumulative overdraft from the groundwater stock.²³ 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 over time as the groundwater stock is depleted.

²⁰This invariance assumption is not critical, and demand will be allowed to vary over time in the empirical application.

²¹Water “used” refers to gross water usage since recharge to the aquifer from return flow is modeled explicitly.

²²Surface water from local sources will also be important in empirical applications.

²³If 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.

3 Efficient Water Use

Efficient groundwater mining and project timing can be found by solving the social planner's problem.²⁴ 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

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

where water usage is $Q(t) = q(t)$ for $t < T$ (i.e., before the project is built) and $Q(t) = I + q(t)$ 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, $\dot{S}(t) = q(t) - R - \alpha Q(t)$. The first integral in the planner's objective is discounted net surplus before the project has been built and before water is imported. 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 water project and to utilize it at capacity,²⁵ steady-state water usage is given implicitly by $Q^{ss} = \bar{I} + R + \alpha Q^{ss}$.

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 flow constraint. The first-order conditions for optimal groundwater pumping and project deliveries are

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

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

²⁴The planner's problem presented here is quite similar to that presented in Holland and Moore.

²⁵If construction costs are greater than the surplus from the project, then it is not efficient to build the water project. Furthermore, if the operating cost of importing water is high, then the project may not be used to capacity. For now, assume it is efficient to build the project and import water at capacity.

$$\dot{\lambda}(t) - r\lambda(t) = -c'(S(t))q(t) \quad (4)$$

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.²⁶ 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) is the equation of motion for the shadow value. Since the growth rate of the shadow value is $r - \frac{c'q}{\lambda}$, the Hotelling r -percent rule takes into account the effect of pumping today on pumping costs in the future.²⁷ In the steady state, the current shadow value is constant, i.e., $\dot{\lambda} = 0$. Equation (4) implies that the steady-state scarcity cost of water is $\frac{c'q}{r}$, which is the marginal increment to the total pumping cost from pumping an additional unit of groundwater capitalized at rate r . Equation (2) then implies that cumulative overdraft in the steady state, S^{ss} , is given by

$$U'(Q^{ss}) = c(S^{ss}) + \frac{c'(S^{ss})}{r}(1 - \alpha)q^{ss} \quad (5)$$

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 paths $Q(t)$ and $q(t)$ need not be continuous at T . Define the superscripts $-$ and $+$ to indicate the limits of these paths before and after T , e.g., $Q^- \equiv \lim_{t \uparrow T} Q(t)$ and $Q^+ \equiv \lim_{t \downarrow T} Q(t)$. The first-order condition for optimal project timing can be written:²⁸

²⁶Alternatively, 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.

²⁷As 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.

²⁸This is equivalent to the condition, $H^- + rF = H^+$, derived by Hartwick *et al.* (1986). See also Holland and Moore.

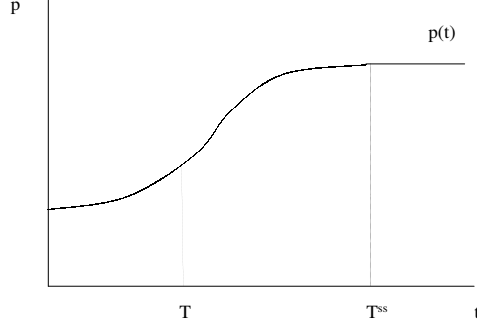


Figure 1: Continuous marginal benefit (price) path. The water-import project is built when the price reaches the trigger price $p^*(t) = c_I + \frac{rF}{T} - \alpha\lambda(T)$.

$$\begin{aligned}
 & U(Q^-) + \alpha\lambda(T)Q^- - (c(S) + \lambda(T))q^- + rF \\
 & = U(Q^+) + \alpha\lambda(T)Q^+ - (c(S) + \lambda(T))q^+ - c_I I
 \end{aligned} \tag{6}$$

Note that the first three terms are the gross benefit 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.

The solution to the planner's problem can be illustrated with the marginal benefit path $p^*(t) \equiv U'(Q^*(t))$ where $Q^*(t)$ is the efficient water usage. If $c_I + \frac{rF}{T} < U'(Q^{ss})$ (i.e., if the project costs are not too large), Holland (2003) shows that $p(t)$ is continuous.²⁹ When the steady state is reached at time T^{ss} , the price is constant at $p^*(T^{ss}) = U'(Q^{ss})$ and groundwater mining ceases. This price path $p^*(t)$ is illustrated in Figure 1. Using this price path, the water usage and extraction paths can be found from the marginal valuation curve. Since the price path is

²⁹Due to the non-convex production sets (caused by the set-up cost), the marginal benefit path need not be continuous. If the costs of the project were large, it would be optimal to pump groundwater beyond the steady-state level before the project is constructed. Once the project is constructed, it would no longer be efficient to pump all the recharge and thus the cumulative overdraft, $S(t)$, would decrease to the steady-state level. In this case, the marginal benefit path would not be continuous at T .

continuous, the usage path is continuous. However, groundwater pumping is discontinuous at T when water importation commences. This discontinuous decrease in groundwater pumping is precisely offset by the discontinuous increase in water importation, so that water usage does not jump.

The efficient time to construct the water-import project can be easily interpreted if $c_I + \frac{rF}{T} < U'(Q^{ss})$. Since $p^*(t)$ is then continuous, water usage is continuous at T , i.e., $Q^- = Q^+$. Thus $q^- = q^+ + I$ and equation (6) imply $c(S) + \lambda(T) = c_I + \frac{rF}{T}$ which—with equation (2)—then implies

$$p^*(T) = c_I + \frac{rF}{T} - \alpha\lambda(T) \quad (7)$$

Define the *trigger price* as the water price (marginal benefit) at which the project is built. Since $p^*(t)$ increases over time, it eventually reaches the trigger price, $p^*(T) = c_I + \frac{rF}{T} - \alpha\lambda(T)$, at which time it is efficient to construct the water-import project. The trigger price shows that the efficient time to construct the water-import project 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.

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 seeks to maximize the following profit function:

$$\int_T^\infty e^{-rt} I[p(t) - c_I] dt - e^{-rT} F \quad (8)$$

where the optimization is 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.³⁰

Consider several alternate assumptions about price formation. Groundwater owners are assumed either to pump groundwater as private property or as a common pool under free access.³¹ 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.³² 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 can be combined into four scenarios: *Scenario 1*, groundwater owners pump groundwater as private property and the project owner is a price taker; *Scenario 2*, groundwater owners pump groundwater as private property and the project owner exercises market power;³³ *Scenario 3*, groundwater owners pump groundwater as a common-pool resource and the project owner is a price taker; and *Scenario 4*, groundwater owners pump groundwater as a common-pool resource and the project owner exercises market power. The subscripts 1-4 will denote the equilibrium values for each of these four scenarios.

First, consider competitive groundwater extraction with well-defined property rights as in Scenarios 1 & 2. Each pumper chooses $q(t)$ to maximize profits:

$$\int_0^{\infty} e^{-rt} q(t) [p(t) - c(S)] dt \quad (9)$$

subject to the equation of motion for cumulative overdraft $\dot{S}(t) = q(t) - R - \alpha Q(t)$. The first

³⁰In 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.

³¹The common-pool assumption refers to common property under free access and should not be confused with collective ownership and management.

³²If 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.

³³Scenario 2 is the only scenario which may be dynamically inconsistent.

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. Note that the growth rate of $p(t)$ is identical to the growth rate of the efficient price path contingent on pumping and imports. The equilibrium price path in Scenarios 1 & 2 is then the price path for which demand equals supply.

Next, consider the price being set by the groundwater extractors pumping from the aquifer as a common pool resource as in Scenarios 3 & 4. As explained above, the pumpers can reasonably be modeled as dissipating rent in each period since groundwater ownership is dispersed among many pumpers. 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 8 where $p(t)$ is exogenous, and optimization is with respect to T and I . Taking the price path as given, the first order conditions for the water project owner are:

$$[p(t) - c_I] - \mu(t) \leq 0 \quad (10)$$

$$I[p(T) - c_I] = rF \quad (11)$$

Equation 10 implies that price should equal marginal cost if water imports are below capacity and that imports should be at capacity if price is above marginal cost. Equation 11 indicates that $p(T) > c_I$. This, when combined with equation 10 and the complementary slackness conditions, implies that project deliveries should be at capacity when the project is constructed.³⁴ Equation 11 can be re-written as $p(T) = c_I + \frac{rF}{I}$. This is the trigger price at which the owner would construct the project in Scenarios 1 & 3. Note that this trigger price is higher than the efficient trigger price.

³⁴This requires that $D(c_I + \frac{rF}{I}) > \bar{I}$.

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 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 of the project or by restricting deliveries.

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 8 except now the price path is an endogenous function of cumulative overdraft.³⁵ Let $\gamma(t)$ be the shadow value to the project owner of a marginal increment of cumulative overdraft.³⁶ Since $q = D(p(t)) - I$ where D is the demand function, the equation of motion can be written $\dot{S}(t) = (1 - \alpha)D(p(t)) - I - R$.³⁷ The project owner thus chooses I and T to optimize equation 8 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

$$p(t) - c_I - \gamma(t) - \mu(t) \leq 0 \quad (12)$$

$$-I[p(T) - c_I] + rF + \gamma(T)I \leq 0 \quad (13)$$

$$\dot{\gamma} - r\gamma = -[I + \gamma(t)(1 - \alpha)D'(p(t))]\frac{dp(t)}{dS} \quad (14)$$

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

³⁵The competitive fringe essentially enforces $p(t)$ as a price cap in period t . A more general analysis would recognize that the project owner may wish to deliver so much that no groundwater is pumped. This case is not analyzed.

³⁶An increment to cumulative overdraft increases the price of water, so γ is positive.

³⁷The 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 consumption because the competitive groundwater owners are the marginal suppliers.

the opportunity cost of an additional unit of cumulative overdraft, γ , plus the capacity cost, μ . Thus equation 12 equates marginal revenue with the marginal cost of water imports. Note that equation 12 implies that deliveries are positive only if $p(t) > c_I$. Equation 13 implies that $p(T) - c_I - \gamma(T)$ is positive. Equation 12 then implies that project deliveries are at capacity at T ,³⁸ and the trigger price for Scenarios 2 & 4 is

$$p(T) = c_I + \frac{rF}{\bar{I}} + \gamma(T) \quad (15)$$

Note that this trigger price is higher than the efficient trigger price and higher than the trigger price in Scenarios 1 & 3.

If capacity is sufficiently scarce such that the project owner would not restrict water deliveries below capacity to drive up the price of water, then the four equilibria can be compared as follows:

Proposition 1 *If project delivery capacity is sufficiently limited, the trigger prices, construction times, and steady-state cumulative overdrafts in the scenarios can be compared as follows:*

$$p^*(T^*) < p_1(T_1) = p_3(T_3) < \min\{p_2(T_2), p_4(T_4)\} \quad (16)$$

$$T^* < T_1 < T_2 \quad \text{and} \quad T_3 < T_4 \quad (17)$$

$$S^{ss*} = S_1^{ss} = S_2^{ss} < S_3^{ss} = S_4^{ss} \quad (18)$$

Proof: The trigger prices $p_1(T_1) = p_3(T_3) = c_I + \frac{rF}{\bar{I}}$ are derived from equation 11. The efficient trigger price, given in equation 7, is smaller since $-\alpha\lambda(T)$ is negative. Similarly, the trigger prices for assumptions 2 and 4, given in equation 15, 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 $\lambda^{ss*} = \frac{c'(S^{ss*})}{r}[D(p^{ss*}) - \bar{I}]$, $(1 - \alpha)D(p^{ss*}) = \bar{I} + R$, and $p^{ss*} = c(S^{ss*}) + (1 - \alpha)\lambda^{ss*}$. Since the steady-states in scenarios 1 and

³⁸For this condition to hold, $D(p(T))$ must be greater than \bar{I} . A necessary condition for this to hold is that $D(c_I + \frac{rF}{\bar{I}}) > \bar{I}$.

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 $(1 - \alpha)D(c(S_3^{ss})) = \bar{I} + R = (1 - \alpha)D(c(S_4^{ss}))$ 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 $S_3^{ss} > S^{ss*}$. ■

Proposition 1 demonstrates the inefficiency resulting from the return-flow externality and from market power. 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., $T_3 < T_4$.³⁹ Comparison of the steady-states show that the market failures have no effect on the steady-state cumulative overdraft when groundwater is pumped as private property, i.e., $S^{ss*} = S_1^{ss} = S_2^{ss}$. This suggests that the deadweight loss from the market failures will be limited. The steady-state cumulative overdraft is higher in the common-pool scenarios, i.e., $S^{ss*} < S_3^{ss} = S_4^{ss}$, but this inefficiency is more properly attributed to the inefficiency of a common pool under free access.

Although Proposition 1 suggests the harm from the market failures might be quite small, the proposition assumes that the project owner builds the efficient delivery capacity and fully utilizes the delivery capacity of the project.⁴⁰ However, the project owner may not have an incentive to build the efficient project capacity. Holland (2003) shows that the incentive to build capacity is found by integrating the shadow values of capacity.⁴¹ Thus the size of the project, constructed at time T , will depend on the discounted current value shadow values, i.e., $\int_0^\infty e^{-rt} \mu(t +$

³⁹The construction times in the common-pool scenarios cannot be compared theoretically with the efficient construction time because the price path is lower.

⁴⁰Sufficient conditions for full utilization of the project will be developed below.

⁴¹The analogous result from the peak-load pricing literature is that the capital payment should equal the sum of the shadow values in a discrete time model. See also Campbell (1980), Holland and Holland and Moore for similar results in exhaustible resource models.

$T)dt$. These shadow values can be compared:

Proposition 2 *If $c'' = 0$ and $\dot{\gamma} \geq 0$, then the incentive to build capacity under the four scenarios can be compared*

$$\int_0^\infty e^{-rt} \mu^*(T^* + t) dt > \int_0^\infty e^{-rt} \mu_1(T_1 + t) dt > \int_0^\infty e^{-rt} \mu_2(T_2 + t) dt \quad (19)$$

$$\int_0^\infty e^{-rt} \mu_3(T_3 + t) dt > \int_0^\infty e^{-rt} \mu_4(T_4 + t) dt \quad (20)$$

Proof: First note that equations 3, 7, and 10-13 imply that $\mu^*(T^*) = \mu_i(T_i) = \frac{rF}{T}$ 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 the present value of $\dot{\lambda} - r\lambda = -c'(S)q$ can be integrated, which shows that the shadow value of groundwater to the pumpers is

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

since $e^{-\infty} \lambda_i^{ss} = 0$. Note that this implies

$$\lambda_i(T_i + t) = \int_t^\infty e^{-r(s-t)} c'(S_i(T_i + s)) q_i(T_i + s) ds. \quad (21)$$

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 $c'' = 0$, equation 21 implies $\lambda^*(T^* + t) > \lambda_1(T_1 + t) > \lambda_2(T_2 + t)$. Next note that $\dot{p}_i = c'(S_i)\dot{S} + \dot{\lambda}_i(1 - \alpha) = c'(S_i)(q - R - \alpha Q - (1 - \alpha)q) + r\lambda_i(1 - \alpha) = c'(S_i)(-R - \alpha\bar{I}) + r\lambda_i(1 - \alpha)$ with a similar equation for \dot{p}^* . Since R and \bar{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 $\dot{\mu}^*(T^* + t) = \dot{p}^*(T^* + t) > \dot{p}_1(T_1 + t) = \dot{\mu}_1(T_1 + t) > \dot{p}_2(T_2 + t) > \dot{p}_2(T_2 + t) - \dot{\gamma}_2(T_2 + t) = \dot{\mu}_2(T_2 + t)$. Since $\mu^*(T^*) = \mu_1(T_1) = \mu_2(T_2)$, this implies $\mu^*(T^* + t) > \mu_1(T_1 + t) > \mu_2(T_2 + t)$. The comparison of the integrals in equation 19 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 $t > 0$. ■

Proposition 2 shows that both the return-flow externality and market power decrease the incentive of the monopoly project owner to build capacity in the water project. The first inequality in Equation 19 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. The second inequality in Equation 19 shows that market power decreases the incentive further, and the monopoly project owner would build even less delivery capacity. Equation 20 shows the analogous result when groundwater is pumped as a common pool or, equivalently, when aquifer transmissivity is high.

If the project owner is a price taker, as in Scenarios 1 & 3, a sufficient condition for full capacity utilization is that $D(c_I + \frac{rF}{I}) > \bar{I}$. When the project owner exerts market power, a sufficient condition is less obvious. To characterize the equilibrium for Scenarios 2 & 4, it is useful to derive the extraction paths when capacity is unlimited and costless to install.

If capacity is unlimited and costless to install, the equilibrium is given by the price path and equations 12 and 14 where $\mu(t) = 0$ for all t . 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 $\dot{\lambda}(t) - r\lambda(t) = -c'(S(t))[D(p_2(t)) - I]$. In equilibrium, $\gamma(t) = p_2(t) - c_I$ so that $\dot{\gamma} = \dot{p} = c'(S)\dot{S} + (1 - \alpha)\dot{\lambda} = r[p_2(t) - c(S)] + c'(S)[- \alpha I - R]$. Noting that $\frac{dp_2(t)}{dS} = c'(S)$ and substituting in equation 14 yields

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

which can be solved for I :

$$I = -(p_2(t) - c_I)D'(p_2(t)) + \frac{R}{(1 - \alpha)} + \frac{r(c(S) - c_I)}{(1 - \alpha)c'(S)} \quad (22)$$

Note that the first term of the expression for I is $D(p) - \pi'(p)$ where $\pi(p) = D(p)(p - c_I)$ is the profit function of the water project owner. Thus, if $p_2(t) = c_I$, the first term would be zero, but if

the price were the monopoly price, defined as p^m , the first term would be the monopoly demand.

However, the price will not rise to the monopoly price if capacity is unlimited. To see this, let \hat{p}_2 and \hat{S}_2 be the steady-state values of p_2 and S_2 when capacity is unlimited and costless to install.⁴² The steady state can be found by setting $\dot{S} = 0$ and $\dot{\gamma} = 0$ in equation 14. This implies:⁴³

$$(1 - \alpha)\pi'(\hat{p}) = R + \frac{r(\hat{p} - c_I)}{c'(\hat{S})} \quad (23)$$

Define $g(S) = (1 - \alpha)\pi'(c(S) + \lambda(1 - \alpha))$, i.e., the left side of equation 23 and $h(S) = R + \frac{r(c(S) + \lambda(1 - \alpha) - c_I)}{c'(S)}$, i.e., the right side of equation 23. Under mild conditions $g' < 0$ and $h' > 0$. This implies that there is a unique \hat{S}_2 for which $g(\hat{S}_2) = h(\hat{S}_2)$ and equation 23 holds. Note that \hat{p} is less than the monopoly price, p^m , since $\pi'(\hat{p}) > 0$.

In Scenario 4, the price path is $p_4(t) = c(S)$. As above, the equilibrium when capacity is unlimited and costless to install is given by equations 12 and 14 where $\mu(t) = 0$. If $I > 0$, 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 14 can now be written:

$$c'(S)[(1 - \alpha)D(c(S)) - I - R] - r(c(S) - c_I) = -c'(S)[I + (c(S) - c_I)(1 - \alpha)D'(c(S))] \quad (24)$$

which can be written

$$(1 - \alpha)[D(c(S)) + (c(S) - c_I)D'(c(S))] = R + \frac{r(c(S) - c_I)}{c'(S)} \quad (25)$$

As above, this equation can be written:

$$(1 - \alpha)\pi'(c(S)) = R + \frac{r(c(S) - c_I)}{c'(S)} \quad (26)$$

Note that equation 26 implies that the price is always below the monopoly price for the water project owner since $\pi' > 0$

⁴²Similarly, let 'hats,' e.g., \hat{p} , denote the steady-state values which would result if capacity were unlimited and costless to install.

⁴³The steady state is fully specified by the equation 23, $\hat{p} = c(\hat{S}) + \lambda(1 - \alpha)$, $\hat{\lambda} = \frac{c'(\hat{S})}{r}[D(\hat{p}) - \hat{I}]$ and $(1 - \alpha)D(\hat{p}) = \hat{I} + R$.

Define $G(S) \equiv (1 - \alpha)\pi'(c(S))$, i.e., the left side of equation 26 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 \hat{S}_4 for which $G(\hat{S}_4) = H(\hat{S}_4)$ and equation 26 holds. Therefore, whenever $I > 0$ the cumulative overdraft must be such that equation 26 holds. If this is the case, the state \hat{S}_4 must be the steady state.⁴⁴ Thus there would be no deliveries from the water project until the cumulative overdraft reached \hat{S}_4 and then project deliveries would be $\hat{I}_4 = (1 - \alpha)D(c(\hat{S}_4)) - R$ if capacity were unlimited and costless to install.

Proposition 3 *If project delivery capacity is unlimited and costless to install, the steady-state prices and cumulative overdraft are such that:*

$$\hat{p}^* < \hat{p}_1 = \hat{p}_3 < \min\{\hat{p}_2, \hat{p}_4\} < \max\{\hat{p}_2, \hat{p}_4\} < p^m \quad (27)$$

$$\hat{S}_1 < \hat{S}_3 \quad \text{and} \quad \max\{\hat{S}_2, \hat{S}_3\} < \hat{S}_4 \quad (28)$$

Proof: From equation 3, the efficient steady-state price is $p^{ss*} = c_I - \alpha\lambda^{ss*}$. In scenarios 1 and 3, the project is constructed when the price equals c_I and the steady state is reached. This implies that $\hat{p}_1 = c_I = \hat{p}_3 > \hat{p}^*$. Next consider equation 26. Since $(1 - \alpha)\pi'(c_I) - R - \frac{r(c_I - c_I)}{c'(S)} = (1 - \alpha)D(c_I) - R > 0$ it follows that $\hat{p}_4 > c_I = \hat{p}_3$. A similar argument based on equation 23 establishes that $\hat{p}_2 > c_I = \hat{p}_1$. Equations 23 and 26 also show that $\pi'(\hat{p}_2) > 0$ and $\pi'(\hat{p}_4) > 0$, so $\max\{\hat{p}_2, \hat{p}_4\} < p^m$.

The steady state in scenario 1 is given by the four equations $\hat{p}_1 = c_I = c(\hat{S}_1) + \hat{\lambda}_1(1 - \alpha)$, $\hat{\lambda}_1 = \frac{c'(\hat{S}_1)}{r}[D(\hat{p}_1) - \hat{I}]$, and $(1 - \alpha)D(\hat{p}_1) = \hat{I}_1 + R$. In scenario 3, the steady state is determined by $c_I = c(\hat{S}_3)$. Thus $c(\hat{S}_3) = c_I = c(\hat{S}_1) + \hat{\lambda}_1(1 - \alpha) > c(\hat{S}_1)$ which implies that $\hat{S}_3 > \hat{S}_1$. Recall that \hat{S}_4 was defined by $G(\hat{S}_4) = H(\hat{S}_4)$. Now $G(\hat{S}_3) = (1 - \alpha)\pi'(c_I) = (1 - \alpha)D(c_I)$. Since $H(\hat{S}_3) = R$ it follows that $G(\hat{S}_3) > H(\hat{S}_3)$ which implies that $\hat{S}_3 < \hat{S}_4$. Finally, since \hat{S}_2 is defined by $g(\hat{S}_2) = h(\hat{S}_2)$ and $g(S) < G(S)$ and $h(S) > H(S)$ for every S , it follows that $\hat{S}_2 < \hat{S}_4$. ■

Proposition 3 has two purposes. First, the steady states which would attain if capacity were unlimited and costless to install can be used to describe sufficient conditions for proposition 1. In particular, if $D(p^m) > \bar{I}$, the monopoly project owner with costly capacity installation would not have an incentive to withhold water deliveries in the steady state. The condition $D(p^m) > \bar{I}$

⁴⁴Substituting $\dot{\gamma} = 0$ in equation 14 demonstrates that equation 26 indeed holds in the steady state.

ensures that marginal revenue of delivering water at capacity is greater than the marginal cost. The additional condition $D(c + \frac{rF}{T}) > \bar{I}$ ensures that the project owner can recover capital costs of the project. These two conditions make precise the phrase “sufficiently limited” in proposition 1.

Second, proposition 3 demonstrates the inefficiencies of the return-flow externality and market power when costs of capacity installation are not important. Equation 27 is analogous to the comparison of trigger prices in Proposition 1. Similarly, the steady-state prices here indicate that the return-flow externality causes the water deliveries to begin at too high a price, i.e., $\hat{p}^* < \hat{p}_1 = \hat{p}_3$, and that market power exacerbates this effect. Although the steady-state cumulative overdraft comparisons are less complete than above, the comparisons indicate inefficiency from market power. Since differences in steady-state cumulative overdraft likely correspond with large efficiency losses, these differences suggest large losses from market power when capacity is costless to install.

5 Numerical Comparison of Steady States

Propositions 1-3 describe the potential inefficiencies from the recharge externality and market power but do not compare all scenarios. Tables 1 and 2 compare all the steady states in a simple numerical example. In the example, the basic parameters of the model are $D(p) = 100 - p$, $c_I = \$20$, $c(S) = \$0.05 \cdot S$, $R = 15$, $\alpha = 0.25$, and $r = 0.1$. Table 1 illustrates proposition 1 where the delivery capacity of the project is constrained to be less than 30 units. Table 2 illustrates proposition 3 where delivery capacity is not constrained. In both cases, the capital costs of constructing the project are ignored.

Since the project’s delivery capacity is limited to 30 units in table 1, the steady-state *consumptive* water use is simply the project deliveries plus exogenous recharge. Thus water use is 60 units and the price is \$40 in the steady-state of each of the five scenarios. Although consumption is

Table 1: **Steady State Comparison** when capacity is limited

	Eff	1	2	3	4
p^{ss}	\$40	\$40	\$40	\$40	\$40
λ^{ss}	\$15	\$15	\$15	0	0
μ^{ss}	\$23.75	\$20	\$9.09	\$20	\$9.09
γ^{ss}	n.a.	n.a.	\$10.91	n.a.	\$10.91
Q^{ss}	60	60	60	60	60
I^{ss}	30	30	30	30	30
S^{ss}	575	575	575	800	800
$c(S^{ss})$	\$28.75	\$28.75	\$28.75	\$40.00	\$40.00
W^{ss}	\$2,738	\$2,738	\$2,738	\$2,400	\$2,400
π^{ss}	\$600	\$600	\$600	\$600	\$600

Notes: “n.a.” means “not applicable”

identical in the scenarios, the marginal pumping cost is higher in scenarios 3 & 4 where groundwater is pumped as a common pool since pumpers compete to capture any groundwater which can be profitably extracted. Thus, in scenarios 3 & 4, the steady-state cumulative overdraft is higher. This illustrates equation 18 of Proposition 1.⁴⁵ The higher pumping cost from larger cumulative overdraft leads to greater inefficiency since steady-state welfare, defined as W^{ss} , is lower.

Proposition 2 is also illustrated in Table 1. The steady-state shadow value of capacity, μ^{ss} , is lower than the efficient value in all the scenarios. This reflects the diminished incentive to build capacity due to the return-flow externality. The result that market power further lessens the incentive to build capacity is illustrated by the fact that μ^{ss} is still smaller in scenarios 2 & 4 where the project owner exerts market power.

⁴⁵Equations 16 and 17 from Proposition 1 are not illustrated in the example since they depend on the time path of pumping and not just the steady state.

Table 2: **Steady State Comparison** when capacity is not limited

	Eff	1	2	3	4
p^{ss}	\$15.48	\$20.00	\$32.86	\$20.00	\$32.86
λ^{ss}	\$18.06	\$17.50	\$15.89	0	0
γ^{ss}	n.a.	n.a.	\$12.86	n.a.	\$12.86
Q^{ss}	84.5	80.0	67.1	80.0	67.1
I^{ss}	48.4	45.0	35.4	45.0	35.4
S^{ss}	38.7	137.5	418.8	200.0	657.1
$c(S^{ss})$	\$1.94	\$6.88	\$20.94	\$20.00	\$32.86
W^{ss}	\$3,842	\$3,659	\$3,088	\$3,200	\$2,709
π^{ss}	-\$219	\$0	\$455	\$0	\$455

Notes: “n.a.” means “not applicable”

Table 2 illustrates proposition 3 showing the potential for inefficiency in the steady state when the project’s delivery capacity is large enough to satisfy demand. The prices and steady state in this example illustrate equations 27 and 28 in Proposition 3.⁴⁶ In scenarios 1 & 3, the steady-state price is determined by the competitive price of delivering project water. Scenario 3 is then completely defined by steady-state cumulative overdraft which implies a pumping cost of \$20. In scenario 1, avoiding the common-pool inefficiency implies a positive shadow value of groundwater, lower pumping costs, and higher welfare in the steady state. The efficient scenario has a lower steady-state price since the marginal percolation benefit is recognized. This implies that water project deliveries are higher and that cumulative overdraft and pumping costs are smaller. Note that in the efficient scenario, the owner of the water project would earn negative profits since the price is below the marginal cost of deliveries.⁴⁷

⁴⁶The results are calculated by solving the relevant system of equations as given in the proof of Proposition 3.

⁴⁷A Pigouvian subsidy of \$4.52 could correct the return-flow inefficiency in the absence of market power.

If project deliveries are unconstrained, the monopoly project owner may wish to raise the steady-state price above the competitive level as illustrated in scenarios 2 & 4. Note that the project owner increases the price by restricting project deliveries substantially. Although the monopoly prices are equal in these two illustrations, they need not be equal in general. Since the monopoly prices are equal, the profits are also equal. However the scenarios differ significantly in cumulative overdraft, pumping costs, and welfare loss.

These numerical examples only compare the steady states and therefore cannot illustrate the dynamic inefficiency. In the private-property case, Table 1 shows no deadweight loss from market power or the return-flow externality in the steady state. However, inefficient trigger prices and construction timing (as shown in Proposition 1) indicate that there is indeed deadweight loss in these scenarios. To show this deadweight loss, the dynamic extraction paths must be calculated. The dynamic deadweight loss is illustrated in the empirical application below.

6 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). CAP imports water from the Colorado River to central Arizona. Fourteen pumping stations lift water 2,400 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 deadweight loss of \$2.6 billion from the inefficient construction. The model of private construction is parameterized below so that the inefficiencies of private construction can be compared to Holland and Moore's

estimate of the inefficiency of public construction.

The following parameterization of water demand and supply follows Holland and Moore directly.⁴⁸ Agricultural demand is assumed to be linear and constant over time with a choke price of \$501.26 per acre-foot. Municipal and industrial demand is also linear but shifts as population grows and has a constant choke price of \$1,793.92. 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. 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.

If the CAP owner delivered water at capacity, the steady-state price would be \$1,142.87. If CAP deliveries were not limited, the steady-state monopoly price would be \$1,034.62 which implies $D(p^m) > \bar{I}$. Since $c_I + \frac{rF}{I} = \$438$, it follows that $D(c_I + \frac{rF}{I}) > \bar{I}$. Thus CAP capacity is “sufficiently limited,” and the hypothetical CAP owner delivers water at capacity.

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 stops. When the CAP is constructed

⁴⁸See Holland and Moore for further details of the model parameterization.

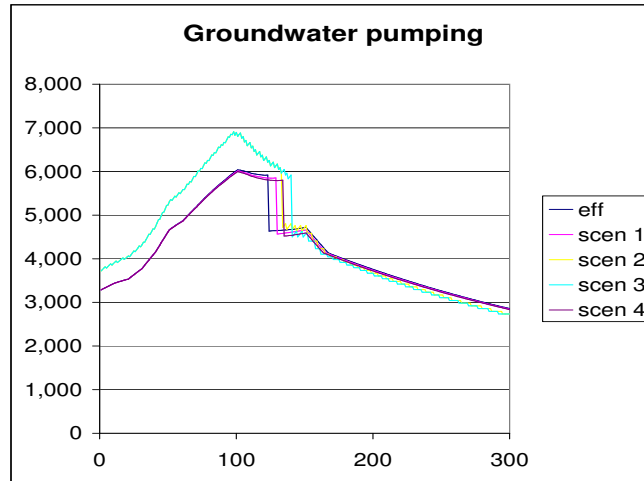


Figure 2: Annual groundwater pumping in kilo-acre-feet (kaf) under the five simulation scenarios.

in each of the scenarios, groundwater pumping jumps down to offset CAP deliveries. In the five scenarios pictured, the CAP is constructed between 2073 and 2098 which are 123 to 148 years after the start of the program.

In Figure 2, only two paths are 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 3. Proposition 1 is illustrated by the construction times, trigger prices and steady-state pumping heights. As shown in equation 16, 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.

The construction times illustrate equation 17 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 3 illustrate equation 18 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 3 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

Table 3: **Simulation results for the Central Arizona Project**

	Construction	Trigger	Welfare	DWL	Profit	Pumping
	Year	Price		(\$ bill)	(\$ mill)	Height (ft)
Efficient*	2073	\$381.19	\$74.172	none	\$1,552.273	6216
Scen 1	2088	\$438.39	\$74.163	\$0.009	\$1,569.365	6216
Scen 2	2095	\$465.54	\$74.156	\$0.015	\$1,570.622	6216
Scen 3	2091	\$438.39	\$73.324	\$0.848	\$1,571.478	6361
Scen 4	2098	\$469.32	\$73.310	\$0.862	\$1,573.039	6361
ComProp*	2062	\$293.06	\$73.362	\$0.810	\$1,492.613	6361
Build 1987*	1987	\$118.35	\$71.560	\$2.612	-\$1,732.651	6216
Zero Profit	2005	\$158.71	\$73.054	\$1.118	\$40.953	6216
Subsidy ZeroProf	1967	\$79.11	\$68.045	\$6.126	\$22.027	6216

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

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 3. 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 “ComProp” scenario reported in Table 3. 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, approximately 56% of the deadweight loss comes from the return-flow externality whereas 44% comes from market power. Comparing scenarios 3 & 4 to the ComProp baseline shows that \$38 million out of the additional deadweight loss of \$52 million (i.e., 74%) 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.

This comparison, however, ignores 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 be much larger. A comparison of the steady-state inefficiencies from Table 2, in which the monopoly project owner does restrict deliveries, shows that approximately 24% of the deadweight loss in the steady state (\$183 out of \$754) comes from the return-flow externality whereas 76% comes from market power. Thus, losses from market power would be much larger if the project owner could reduce capital costs by constructing smaller delivery capacity in the project.

The deadweight loss of \$810 million in the ComProp scenario in Table 3 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 ComProp scenario of \$810 million. This suggests that the inefficiencies from the return-flow externality and market power are much smaller than the inefficiency that results from the inability of aquifer pumpers to exclude other users from pumping the groundwater in which they hold property rights. However, the common-pool scenarios likely

overestimate the loss from poorly defined groundwater rights since the scenarios assume complete spillovers. The scenarios assume that the water table is lowered equally under all landowners when water is pumped by any individual landowner. In practice, the aquifer is drawn down disproportionately under the landowner who pumps the groundwater, especially in an aquifer with low transmissivity. Assuming complete spillovers overestimates the inefficiency of the common-pool scenarios.

The most dramatic comparison in Table 3 is with Holland and Moore's estimate of the deadweight loss from actual construction. They estimated that construction by the Bureau of Reclamation with deliveries beginning in 1987 occurred 86 years too early with a deadweight loss of \$2.612 billion. 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.⁴⁹ 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.⁵⁰ With insecure property rights and federal subsidies, the firm would construct the project

⁴⁹California was using some of Arizona's allocation of Colorado River water and tried to establish ownership under the prior appropriation doctrine.

⁵⁰This construction date may imply many years of operating losses in order to establish the property right.

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 3, 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 an policy environment of federal subsidies and insecure property rights.

A final interesting point to note in Table 3 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.⁵¹

7 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 the traditional problems from market failure. 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

⁵¹The additional profit from market power is not large. In all scenarios, the profit from market power increases profit by less than 2%.

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 the return-flow externality leads the project to be constructed later than optimal when the price of groundwater is higher than optimal. This result obtains 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 incentive of the project owner to install capacity in the project. In summary, the theoretical results indicate that private incentives result in too little capacity being built and the construction date being later than optimal when the price of water is too high.

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 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. 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 million) is much 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.⁵² However, the estimated deadweight loss of the common-pool scenarios likely overstates the loss from poorly defined groundwater 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, spillovers 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.

Comparing the estimated deadweight loss from hypothetical private construction with public construction shows much 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 much 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 outcome—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 sub-

⁵²Policy 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.

sidies and insecure property rights that surrounded the CAP construction. In this policy environment, I estimate that private construction would have led to similarly large inefficiencies (estimated at \$6.1 billion). 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.

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.

References

- [1] Albiac-Murillo, Jose, Javier Tapia-Barcones, Anika Meyer and Javier Uche, "Water Demand Alternatives to the Spanish National Plan." Paper presented at the Second World Congress of Environmental and Resource Economists, Monterey CA 2002.
- [2] Anderson, Terry, *Water Crisis: Ending the Policy Drought*, (Washington, D.C.: Cato Institute), 1983.
- [3] Bain, J. S., R. E. Caves, and J. Margolis, *Northern California's Water Industry: The Comparative Efficiency of Public Enterprise in Developing a Scarce Natural Resource* (Washington, D.C.: Resources for the Future), 1966.
- [4] Bauer, Carl, "Bringing Water Markets Down to Earth: The Political Economy of Water Rights in Chile, 1976-95" *World Development* 25 (1997): 639-56.
- [5] Beesley, M. E., "Mergers and Water Regulation," in Beesley, M. E. ed. *Privatization, Regulation and Deregulation* (New York and London: Routledge), 1997, pp 84-92.
- [6] Bhattacharyya, Arunava, Elliott Parker, Kambiz Raffiee, "An Examination of the Effect of Ownership on the Relative Efficiency of Public and Private Water Utilities," *Land Economics* 70 (1994): 197-209.
- [7] Borenstein, Severin, James Bushnell, and Frank Wolak, "Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market" *American Economic Review* 92(2002):1376-1405.
- [8] Brooks, R., J. Controneo, M. Murray, and S. Salant, "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 (Aug. 1999):843-858.
- [9] Bruggink, Thomas, "Privatization versus Groundwater Central Management: Public Policy Choices to Prevent a Water Crisis in the 1990s," *American Journal of Economics and Sociology* 51(1992): 205-22.
- [10] Campbell, Harry F., "The Effect of Capital Intensity on the Optimal Rate of Extraction of a Mineral Deposit" *The Canadian Journal of Economics*, 13(2), pp. 349-356, 1980.
- [11] Cowan, Simon, "The Water Industry," in Helm, Dieter and Tim Jenkinson eds. *Competition in regulated industries*, (Oxford and New York: Oxford University Press), 1998: 160-74.
- [12] Cowen, Penelope and Tyler Cowen, "Deregulated Private Water Supply: A Policy Option for Developing Countries," *Cato Journal* 18 (1998): 21-41.
- [13] Eckstein, Otto, *Water-Resource Development: The Economics of Project Evaluation* (Cambridge, MA: Harvard University Press), 1958.
- [14] Freeman, A. Myrick, III, "Adjusted Benefit-Cost Ratios for Six Recent Reclamation Projects," *Journal of Farm Economics*, 48 (November 1966): 1002-1012.
- [15] Gilbert, Richard, "Dominant Firm Pricing Policy in a Market for an Exhaustible Resource," *Bell Journal of Economics*, 9 (1978): 385-395.

- [16] Hahn, Robert W., "Market Power and Transferable Property Rights" *Quarterly Journal of Economics*, 99(1984): 753-65.
- [17] Hartwick, J.M., M.C. Kemp, and N.V. Long, "Set-Up Costs and Theory of Exhaustible Resources," *Journal of Environmental Economics and Management*, 13(1986): 212-224.
- [18] Hirshleifer, J., J. C. DeHaven, and J. W. Milliman, *Water Supply: Economics, Technology, and Policy* (Chicago: The University of Chicago Press), 1960.
- [19] Holland, Stephen P., "Set-up Costs and the Existence of Competitive Equilibria when Extraction Capacity Is Limited," *Journal of Environmental Economics and Management* 46(2003):539-55.
- [20] Holland, Stephen and Michael R. Moore, "Cadillac Desert Revisited: Property Rights, Public Policy, and Water-Resource Depletion," *Journal of Environmental Economics and Management* 46(2003):131-55.
- [21] Joskow, Paul L. and Edward Kahn, "A Quantitative Analysis of Pricing Behavior in California's Wholesale Electricity Market During Summer 2000," *Energy Journal*, 23(2002):1-35.
- [22] Lee, Terence, *Water Management in the Twenty-first Century: The Allocation Imperative*, (Cheltenham, U.K. and Northampton, Mass.: Elgar), 1999.
- [23] Lee, Jee Hoon, Stephen Polasky, and Jay Coggins, "Marketable Emissions Permits With Large Firmst or a Large Market," mimeo, 2002.
- [24] Lewis, Tracy R. and Richard Schmalensee, "On Oligopolistic Markets for Nonrenewable Natural Resources," *Quarterly Journal of Economics* 95 (1980): 475-491.
- [25] Lewis, Tracy R. and Richard Schmalensee, "Cartel Deception in Nonrenewable Resource Markets," *The Bell Journal of Economics* 13 (1982): 263-271.
- [26] Maskin, Eric and David Newbery, "Disadvantageous Oil Tariffs and Dynamic Consistency," *The American Economic Review* 80(1990): 143-156.
- [27] Newbery, David, "Oil Prices, Cartels, and the Problem of Dynamic Inconsistency," *The Economic Journal* 91 (1981): 617-646.
- [28] Noll, Roger, Mary Shirley, and Simon Cowan. "Reforming Urban Water Systems in Developing Countries," in Krueger, Anne, ed. *Economic Policy Reform: The Second Stage*, (Chicago and London: University of Chicago Press), 2000.
- [29] Ogden, Stuart. "Transforming Frameworks of Accountability: The Case of Water Privatization" Keasey, Kevin, Steve Thompson, and Mike Wright eds. *Corporate Governance: Economic and Financial Issues*, (New York: Oxford University Press), 1997.
- [30] Poole, Robert Jr. and Philip Fixler, Jr. "Privatization of Public-Sector Services in Practice: Experience and Potential," *Journal of Policy Analysis and Management*, 6(1987): 612-25.
- [31] Robson, Arthur. "OPEC Versus the West: A Robust Equilibrium," *Journal of Environmental Economics and Management*, 10 (1983): 18-34.

- [32] Saal, David and David Parker. "Productivity and Price Performance in the Privatized Water and Sewerage Companies of England and Wales," *Journal of Regulatory Economics*, 20(2001): 61-90.
- [33] Salant, Stephen W. "Exhaustible Resources and Industrial Structure: A Nash-Cournot Approach to the World Oil Market," *Journal of Political Economy* 84 (1976): 1079-1093.
- [34] Spulber, Nicolas and Asghar Sabbaghi, *Economics of Water Resources: From Regulation to Privatization*, (London and Dordrecht: Kluwer Academic), 1998.
- [35] Stanislaw, Joseph, and Daniel Yergin, *The Commanding Heights: The Battle Between Government and the Marketplace That Is Remaking the Modern World* (New York, NY: Simon and Schuster), 1998.
- [36] Stiglitz, Joseph and Partha Dasgupta, "Market Structure and Resource Depletion: A Contribution to the Theory of Intertemporal Monopolistic Competition," *Journal of Economic Theory* 28 (1982): 128-164.
- [37] Timmins, Christopher, "Measuring the Dynamic Efficiency Costs of Regulators' Preferences: Municipal Water Utilities in the Arid West," *Econometrica*, 70 (2002):603-629.
- [38] Wahl, Richard W., *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation* (Washington, D.C.: Resources for the Future), 1989.
- [39] World Bank, "Statistics on the World Bank's Dam Portfolio," <www.worldbank.org/html/extdr/pb/dams/factsheet.html>, 2002.
- [40] World Bank, "Water Resources Management," World Bank Policy Paper, 1993.
- [41] "WSTB, A Newsletter from the Water Science and Technology Board," National Research Council, National Academy of Sciences, Vol. 18 #3, Sept./Oct. 2001.