Cadillac Desert Revisited: Property Rights, Public Policy, and Water-Resource Depletion

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February 23, 2001

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*The views expressed in this paper are those of the author and do not necessarily represent the views of the Federal Trade Commission or any individual Commissioner.

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‡The authors thank Stephen Salant, John Laitner, Chad Hogan, Klaas van 't Veld, and Gérard Gaudet. Special thanks to Benjamin Simon, U. S. Department of the Interior, for providing documents on the Central Arizona Project.

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Abstract

Imperfect property rights and government subsidies are pervasive sources of inefficiency in natural resource development. To alleviate central Arizona's dependence on exhaustible groundwater, the federal government subsidized construction of the Central Arizona Project to import up to 1.287 million acre-feet of water per year from the Colorado River. In return for the subsidy, Arizona groundwater law was reformed to eliminate the common-property pumping of groundwater and to ban groundwater mining after the year 2025. We build a model of water resource development in which imported water is a capacity constrained backstop. The model is applied to Arizona's water problem to quantify the welfare effects of alternative CAP construction dates and Arizona groundwater laws.

We reach two general conclusions. First, properly timed, CAP would have increased social surplus by a modest \$69 million compared to the situation where central Arizona had no access to Colorado River water and extracted its groundwater efficiently. However, because of the federal subsidies, Arizona successfully pressed for early construction of CAP. CAP was thus completed 71 years too early, in 1987, at a deadweight loss of \$1.323 billion relative to optimal timing. Ironically, construction in 1987 yielded lower surplus than never constructing CAP. Second, the explicit political exchange of state groundwater reform for federal subsidies and sub-optimal timing introduced a greater loss (\$1.323 billion) than it corrected (\$0.988 billion). Thus, this political exchange—which was initiated as a new federal policy—was worse than doing nothing at all.

> A political mirage for three generations of Arizonans, the Central Arizona Project is now a palpable mirage, as incongruous a spectacle as any on earth: a man-made river flowing uphill in a place of almost no rain... To build something so vast–an aqueduct that may stretch eventually to 333 miles, pumps that will lift the water 1,249 feet, four or five receiving reservoirs to hold the water when it arrives–at a cost that may ultimately reach $3 billion, perhaps even more, would seem to demand two prerequisites: that there be a demand for all the water and that it be available in the first place. In Arizona, all of this has been a blind article of faith for more than half a century. Build the CAP, and the aqueduct will be forever filled because of Arizona's [Colorado River] Compact entitlement; fill the aqueduct, and the water will be put to immediate use–that is what every politician who ever aspired to sainthood in Arizona has said.
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> Marc Reisner, *Cadillac Desert: The American West and Its Disappearing Water*, 1986

1 Introduction

Water law and policy in the American West distort incentives for the development and use of groundwater and surface water resources. First, property rights to water resources defined by a rule-of-capture lead to premature exploitation of water resources. Additionally, limited transferability of these rights prevents water from being allocated to its highest value use. Second, mining of groundwater reserves as a nonrenewable resource is prohibited in some western states. A future ban on mining can lead to a perverse incentive for increased groundwater pumping in advance of the ban. Third, subsidies exacerbate the inefficiencies of water law. The federal Reclamation program's generous subsidy of western water projects distorted project timing throughout the 20th century.[1] In this paper, we develop a model to analyze these inefficiencies of water resource development and apply the model empirically to a quintessential case: the Central Arizona Project.

[1] Historical accounts, such as Reisner's *Cadillac Desert* (1986) and Worster's *Rivers of Empire* (1985), depict federally-subsidized river development as the (flawed) engine of growth throughout the West for most of the 20th century, through 1980. The historian's broad sweep appears to hold larger appeal than the economist's quantitative analysis: in June 1997, the Public Broadcasting System televised Cadillac Desert, a four-part documentary based on Reisner's book of the same name.

Water use in the West frequently involves the intertemporal tradeoff between mining local groundwater and building a project to import water from a distant source. The problem is made complex in that the major laws and policies—common-property groundwater pumping, nontransferable water rights, groundwater mining bans, and Reclamation subsidies—interact to distort demand and supply across water sources. For example, common-property groundwater mining increases demand for imported water since the aquifer is depleted too rapidly. Reclamation subsidies, in turn, distort both groundwater mining and the timing decision on water-project construction. To analyze these distortions, we develop a model of natural resource depletion with a nonrenewable resource (groundwater) and a renewable backstop (imported surface water).[2] The model extends basic results on nonrenewable resource depletion with a backstop (Hotelling 1931; Nordhaus 1973) to analyze two additional features of the backstop: set-up costs and a flow constraint.[3] Set-up costs for constructing dams, aqueducts, and pumping stations must be incurred before any water can be imported. In addition, the flow of imported water is constrained by interstate law, aqueduct size, or river flow.[4]

The solution to the depletion problem is characterized by a Hotelling price path. As the price rises, it reaches a trigger price that covers the project's operating cost plus the interest payment on the set-up cost. The trigger price determines the efficient time

[2]Some elements of this framework were developed earlier for the case of groundwater depletion and surface-water imports (Brown and Deacon 1972; Cummings 1974; Kim and Moore 1989). Many studies have developed Hotelling models of resource depletion and applied the models via simulation. See Chakravorty *et al.* (1997) for a recent example.

[3]Set-up costs create a non-convexity in the production possibilities set, which leads to the nonexistence of a competitive equilibrium in the exhaustible resource problem (Hartwick, Kemp, and Long 1986). However, adding a flow capacity constraint in addition to set-up costs results in conditions under which existence of a competitive equilibrium is preserved (Holland 1999).

[4]See Amigues *et al.* (1998) for analysis of a general equilibrium model of resource depletion with a capacity-constrained backstop and Kim and Moore (1989) for a similar partial equilibrium analysis.

to construct the water-import project. The price then continues to rise before reaching a constant value in a steady state in which groundwater is no longer mined.

In central Arizona, nonrenewable groundwater reserves supported the expansion of irrigated agriculture and the growth of the Phoenix and Tucson metropolitan areas. Groundwater mining in excess of 2 million acre-feet per year has occurred since the 1950's. To augment dwindling groundwater reserves and to establish clear title to water from the Colorado River, Arizonans proposed the Central Arizona Project (CAP) to transport over 1 million acre-feet of water per year from the western border of the state to central Arizona.[5] Construction started in 1973 and deliveries began in 1987. A numerical simulation of the model with parameters on Arizona water demand, supply, and hydrology is developed to assess the effects of several policies. These include: federal subsidies of CAP construction and operating costs; a legal restriction on interstate water marketing under the Colorado River Compact; common-property depletion of Arizona groundwater; and Arizona's 1980 reform of groundwater law, which bans groundwater mining after the year 2025.

Our results shed light on various policy choices. First, we estimate that CAP was built 71 years too early. Due to the relative abundance of groundwater and the high costs of the project, welfare would have increased by delaying the project and using the available groundwater.[6] However, Arizona did not bear the full costs of the project because of federal

[5] Many of the largest federal water projects (both actual and proposed) involved interbasin water transfers as "rescue operations" for regions that were exhausting local groundwater supplies (Howe and Easter 1971). Indeed, a recent commission recommends that federal water-import projects be viewed with skepticism unless efforts are first made to address common-pool depletion of groundwater (Western Water Policy Review Advisory Commission 1998).

[6] A series of studies co-authored by William E. Martin (e.g., Bush and Martin 1986; Ingram, Martin, and Laney 1982) made the point that groundwater would be cheaper than CAP water if CAP construction was timed as planned. Our study is the first to assess optimal CAP timing and the deadweight loss of inefficient policies.

subsidies. From Arizona's perspective, consequently, the project was actually built 16 years too late. Second, although Arizona benefited from CAP, the project did not yield large social benefits. In fact, constructing the project in 1987 yielded lower welfare than if the project had never been built. Third, the relative returns to groundwater management highlight another poor policy choice. The federal government agreed to subsidize CAP only if Arizona reformed its groundwater law. The benefit from removing the common-pool distortion, however, was smaller than the loss introduced by the subsidies. Finally, the deadweight loss from the ban on groundwater mining in 2025 raises doubt about the ban's credibility. As suggested by theory (Long 1975), groundwater pumping prior to 2025 increases in response to the ban. This explains a portion of the deadweight loss, while unused groundwater reserves explain the rest.

The paper continues with a description of the laws and policies that govern western water allocation and a review of the related literature. In contrast to previous research, we analyze the interrelated effects of several laws and policies instead of individual policies in isolation. Section 3 develops the theoretical model, while Section 4 describes the simulation model. The empirical results are reported in two sections. Section 5 studies the value of constructing CAP. Section 6 assesses a political exchange in which reform of Arizona groundwater law was required as a condition of CAP's federal subsidy. A final section concludes and identifies other applications of the modeling framework.

2 Western Water Law and Policy

A governance structure of Reclamation policy, state water laws, and interstate law on shared river systems defines water allocation in the West (Table 1). This structure establishes the empirical setting for the subsequent analysis of policy-induced inefficiencies in water use.

2.1 Federal Reclamation Policy and the CAP

Beginning with the Reclamation Act of 1902, the Bureau of Reclamation pursued its mission of western settlement through an ambitious program to construct and subsidize dams and related irrigation works.[7] Reclamation's subsidies require local beneficiaries to repay only a portion of federal financing of a project's construction costs. Economists have long questioned the subsidies on efficiency grounds (e.g., Bain, Caves, and Margolis 1966; Eckstein 1958; Hirshleifer, DeHaven, and Milliman 1960).[8] In particular, Freeman (1966) finds that costs outweighed benefits for many Reclamation projects, especially those constructed after 1950. Most recently, Wahl (1989) estimated that, for the overall Reclamation program, the capital subsidy rate was 82 percent in 1975.[9]

The CAP is a massive Reclamation project, transporting water over 300 miles from the Colorado River on the western border of Arizona to south-central Arizona. Along the route, a series of pumping plants lift water over 2,000 feet in elevation. CAP's construction costs (approximately \$5 billion) and operating costs (approximately \$220/acre-foot) are subsidized at rates of 52 percent and 61 percent (*see* Appendix 1). With construction costs, Reclamation policy creates various subsidies to the agricultural sector. With operating costs, the federal government sells the electricity required to pump CAP water at a low,

[7]The Reclamation program recorded impressive statistics: construction of 355 storage reservoirs, 255 diversion dams, and 18,000 miles of water-transport facilities. Historians aptly refer to the program with evocative phrases, such as Reisner's *cadillac desert* and Worster's *rivers of empire*.

[8]In addition to the possibility of inefficient capital formation, Stavins and Jaffe (1990) show that public infrastructure investments may produce unintended consequences through related private decisions. They study the case of federal flood-control projects and private depletion of forested wetlands.

[9]In 1977, President Jimmy Carter vetoed nine Reclamation projects with low benefit-cost ratios, an event that observers use to mark the end of the Reclamation program's long period of political power (Worster 1985).

administered price rather than a market price.

Legislation to authorize CAP as a Reclamation project was first introduced into the U.S. Congress in 1947. Legal attacks on Arizona's right to divert Colorado River water impeded CAP authorization until a U.S. Supreme Court decision in 1963. CAP construction then began in 1973. Nevertheless, the Carter Administration twice threatened CAP's completion. CAP made Carter's famous "hit list" of water projects in 1977, only to be later removed from the list after intense negotiation. Again in 1979, the administration pressed Arizona for reform of its groundwater law as a condition of federal cost-sharing on CAP. Arizona relented by adopting a new law in 1980. CAP deliveries finally began in 1987.

2.2 Surface Water Law and the Colorado River Compact

The prior appropriation doctrine provides a legal framework to establish quantity-based rights to surface water in the 17 western states (Sax, Abrams, and Thompson 1991). The Colorado River Compact applies prior appropriation principles to interstate water allocation. The compact apportions the Colorado River among the seven states through which the river flows; Arizona's endowment is 2.2 million acre-feet of water per year. The compact, however, does not create clear title for Arizona; the appropriation doctrine's beneficial use provision stipulates that agents establish tenure certainty in the right only through physical diversion of water.[10] Thus, Arizona's valid title to its full endowment remained uncertain until CAP began delivering water.

Burness and Quirk (1979) find that the prior appropriation doctrine promotes inefficient river development and water use. They proceed to show that a water market could

[10]Sax, Abrams,and Thompson (1991, p. 164) write, "Beneficial use is the measure and the limit of an appropriative right. The right vests when the water is actually applied to use."

correct these inefficiencies (Burness and Quirk 1980). Many empirical studies estimate the gains from trade that could occur with voluntary transfer of water rights (e.g., Booker and Young 1994; Frederick 1986; Vaux and Howitt 1984). Although water markets are now being deregulated within several states, an interstate market has not formed along the Colorado River.[11] The laws governing the river's allocation do not explicitly authorize interstate marketing, and some provisions implicitly prohibit marketing (Pontius 1997).

2.3 State Groundwater Law and Arizona Legal Reform

Across the western states, groundwater is typically depleted as a common-pool resource with a rule-of-capture defining the right to use (Gardner, Moore, and Walker 1997). Theory predicts that agents undertake an inefficiently rapid pace of mining when a rule-of-capture determines groundwater rights (Brown 1974). Several studies estimate the benefit of groundwater management using simulations of common-property depletion (e.g., Feinerman and Knapp 1983; Gisser 1983; Kim, *et al.* 1989).

Arizona law prior to 1980 defined groundwater as a commons; ownership of land overlying an aquifer conveyed an unlimited right to pump water. When considering CAP, federal officials viewed water-import projects as expensive remedies for bad state policy: if the states had developed efficient law, aquifers would not be exhausted so rapidly. For the carrot of the CAP, the Carter Administration wielded a stick: Arizona must reform its groundwater law or Reclamation would not construct CAP (Reisner 1986). Passage of the Arizona Groundwater Management Act of 1980 assured continued federal subsidy of CAP.[12]

[11] An early proposal for *intrastate* marketing of Colorado River water examined potential gains from trade in southern California (Stavins 1983).

[12] The leading textbook on water law labels the Arizona act as "the West's most advanced groundwater statute" (Sax, Abrams, and Thompson 1991, p. 710).

Arizona's 1980 groundwater law has two salient features. First, it created reasonably well defined, transferable property rights in groundwater. The law established: a permit system for groundwater rights with limits on annual depletion; a requirement for metering; an agency for enforcement; and an ability to transfer rights (Arizona DWR 1984a; Saliba and Bush 1987). Second, the law bans groundwater mining beginning January 1, 2025. Mining occurs when net depletion of groundwater exceeds natural recharge. Thus, the law restricts groundwater use to the "safe yield" rate, in which net depletion equals recharge (Arizona DWR 1984a). The cost of a ban on groundwater mining has not been studied empirically. In related theory, however, Long (1975) shows that nationalization of a nonrenewable resource increases extraction in advance of the date of nationalization.

3 The Theoretical Model

Analysis of the tradeoff between groundwater extraction and surface water importation requires a model of the economic behavior of agents and the hydrological effects of their decisions.[13] The analysis allocates water consumption to maximize discounted benefits net of pumping, construction, and operating costs. The model incorporates two important features of a water project: set-up costs and a flow constraint. Water from a distant river can be imported only after expenditures on the project. In addition, the flow of water may be constrained by physical or legal factors.

Let $Q(t)$ be the quantity of water consumed[14] at time t, and $U_t(Q(t))$ be the gross

[13] Although we apply the model to water resources, the techniques are generally applicable to any exhaustible resource whose backstop substitute has limited production and costly capacity installation.

[14] Water consumption here refers to gross water consumption since recharge to the aquifer from percolation is modeled explicitly.

surplus from water at time t where $U_t' > 0$ and $U_t'' < 0$.[15] Water supply comes from three sources: local surface water, imported water, and groundwater. The quantity of local surface water available is L and can be utilized at cost $c_L L$. Let I be the quantity of water available to import from a distant river. If the water is not imported, it has a value of $v_m \geq 0$ per unit.[16] Water can be imported only after construction of a project. Let F be the set-up costs of construction and $c_I I$ be the operating costs of importing I units of water after the project is constructed.

The groundwater is replenished by R units of recharge from precipitation and streamflow and by percolation of the water consumed at a rate $\alpha < 1$.[17] Thus, total recharge to the aquifer is $R + \alpha Q(t)$. If groundwater pumping is greater than total recharge, then groundwater is being "mined." Let $q(t)$ be the quantity of groundwater pumped at t. Hence, the amount of overdraft mined from the aquifer is $q(t) - R - \alpha Q(t)$.[18] 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. 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.

[15] For ease of exposition, the time subscript is dropped from the utility function in all subsequent expressions. Demand will increase over time in the empirical application due to population growth.

[16] v_m is thus the opportunity cost of allocating water to the import project. In this study, v_m will represent solely the monetary gain from selling the water to other users. Since there are likely environmental benefits of leaving water in the river, our results understate the costs of the water-import project.

[17] The recharge, R, is assumed to be non-stochastic. If agents are risk averse and R is stochastic, our analysis will understate the benefits of the water project. Alternatively, if water imports, I, are stochastic and agents risk averse, our results will overstate the benefits of the project.

[18] If pumping is less than recharge, then overdraft is negative and the aquifer is being replenished.

3.1 Efficient Water Use

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

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

where water consumption is $Q(t) = L + q(t)$ for $t < T$ (i.e., before the project is built) and $Q(t) = L + I + q(t)$ for $t > T$. The first integral in the planner's objective is discounted net surplus before the project has been built and before water is imported. Net surplus is the benefit from consuming and marketing water less the costs of pumping groundwater and supplying local surface water. The second term in the objective is the present value of the set-up cost for the project. The final integral is net surplus after the project has been built and water importation has begun. The equation of motion and initial condition of the stock variable are

$$\dot{S}(t) = q(t) - R - \alpha Q(t)$$

$$S(0) = 0$$

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,[19] steady-state consumption is given implicitly by $Q^{ss} = L + I + R + \alpha Q^{ss}$.

[19] If 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. With the parameters of this study, it is efficient to build the project and import water at capacity.

The consumption and extraction paths are found from the first order conditions of the planner's optimization problem. Let $\lambda(t)$ be the shadow value of groundwater defined from the standard current-value Hamiltonian. The first order conditions for optimal groundwater pumping are

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

$$\dot{\lambda}(t) - r\lambda(t) = -c'(S(t))q(t) \tag{3}$$

Since $\lambda(t)$ is the shadow value of an additional unit of groundwater at time t, $\lambda(t)$ is the opportunity (scarcity) cost of pumping an additional unit of groundwater at time t. The term $\alpha\lambda(t)$ is then the marginal percolation benefit of consuming an additional unit of water at time t. Equation (2) thus equates the marginal benefits from consumption and percolation with the marginal pumping and scarcity costs. Equation (3) is the equation of motion of the shadow value. Since the growth rate of the shadow value is $r - \frac{c'q}{\lambda}$, the Hotelling r-percent rule is modified by the effect of pumping today on pumping costs in the future. In the steady state, the current shadow value is constant, i.e., $\dot{\lambda} = 0$. Thus cumulative overdraft in the steady state, S^{ss}, is given by

$$U'(Q^{ss}) = c(S^{ss}) + \frac{c'(S^{ss})}{r}(1-\alpha)q^{ss} \tag{4}$$

where $q^{ss} = R + \alpha Q^{ss}$. That is, the marginal benefit of consumption 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 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 $Q^+ \equiv \lim_{t\downarrow T} Q(t)$. Following

Hartwick *et al.* (1986), the first order condition for optimal project timing, $H^- + rF = H^+$, is

$$e^{-rT}[U(Q^-) - c(S)q^- - c_L L + v_m I - \lambda(T)(q^- - R - \alpha Q^-)] + re^{-rT}F$$
$$- \left\{e^{-rT}[U(Q^+) - c(S)q^+ - c_L L - c_I I - \lambda(T)(q^+ - R - \alpha Q^+)]\right\} = 0 \qquad (5)$$

This equation is derived by constraining the planner's problem in equation (1) with the equation of motion of the stock and differentiating with respect to T. This first order condition can then be written

$$U(Q^-) + \alpha\lambda(T)Q^- - (c(S) + \lambda(T))q^- + rF$$
$$= U(Q^+) + \alpha\lambda(T)Q^+ - (c(S) + \lambda(T))q^+ - (c_I + v_m)I \qquad (6)$$

Note that the first three terms are the gross benefit from consumption and percolation less pumping and scarcity costs. The right hand side is also the net benefit but additionally includes the operating plus opportunity costs 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 price path $p(t) \equiv U'(Q^*(t))$ where $Q^*(t)$ is the efficient consumption of water. If $c_I + v_m + \frac{rF}{I} < U'(Q^{ss})$ (i.e., if the project costs are not too large), Holland (1999) shows that $p(t)$ is continuous and defines a competitive equilibrium price path.[20] When the steady state is reached at time

[20]Due to the non-convex production sets (caused by the set-up cost), the marginal benefit path need not be a competitive equilibrium price. 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.

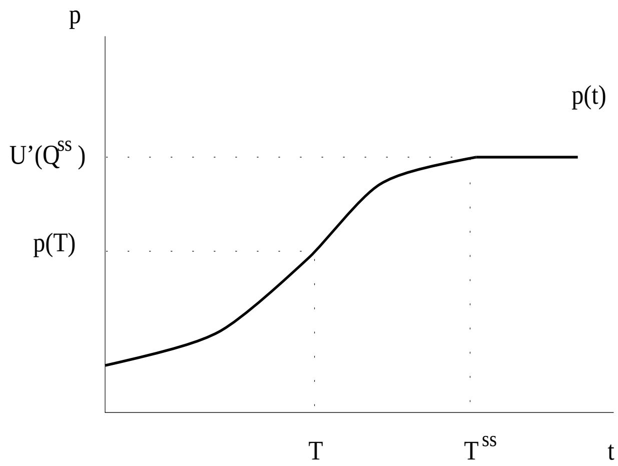

Figure 1: Continuous price path. The water-import project is built when the price reaches the trigger price $p(T) = c_I + v_m + \frac{rF}{I} - \alpha\lambda(T)$.

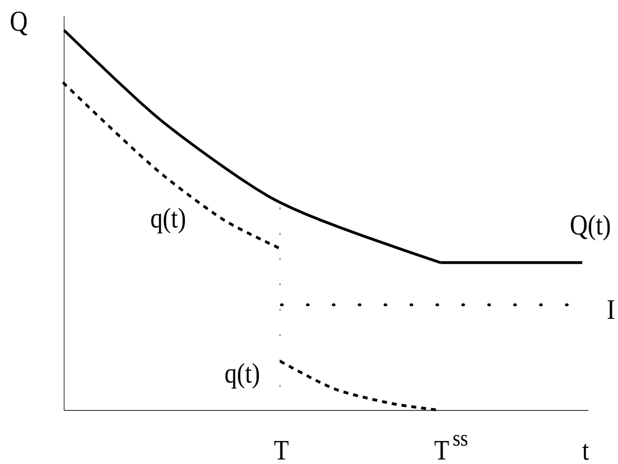

Figure 2: Consumption and extraction paths for a stationary demand curve. Note that the groundwater pumping path, $q(t)$, is discontinuous at T.

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.[21] Using this price path, the consumption and extraction paths can be found from the marginal valuation curve. Consumption and extraction paths for a stationary demand curve are illustrated in Figure 2. Since the price path is increasing and continuous, the consumption path is decreasing and continuous. However, groundwater

[21]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 $\dot{p}(t) = c'(S)[-R - \alpha(L + I)] + r\lambda(t)(1 - \alpha) > 0$. This holds if the increase in the marginal pumping cost is small as cumulative overdraft increases.

pumping is discontinuous at T when water importation commences. Note that between T and T^{ss}, the flow constrained backstop implies that groundwater pumping and water imports occur simultaneously in order to smooth consumption.

The efficient time to construct the water-import project can be easily interpreted if $c_I + v_m + \frac{rF}{I} < U'(Q^{ss})$. Since the price path $p(t)$ is then continuous, consumption is continuous at T, i.e., $Q^- = Q^+$. Thus $q^- = q^+ + I$ and equation (6) can be written

$$c(S) + \lambda(T) = c_I + v_m + \frac{rF}{I} \tag{7}$$

Equation (2) then implies

$$p(T) + \alpha\lambda(T) = c_I + v_m + \frac{rF}{I} \tag{8}$$

Thus the efficient time to construct the water-import project is when the marginal benefit of consumption plus recharge exceeds the marginal importation cost by the per unit interest payment on the set-up cost. As $p(t)$ increases over time, it eventually reaches the "trigger price" $c_I + v_m + \frac{rF}{I} - \alpha\lambda(T)$, at which time the social planner would construct the water-import project.[22]

The efficient construction timing and trigger price are illustrated in Figure 3.[23] The benefit measures in equation (6) can be illustrated explicitly in this figure. For example, the net benefit from percolation and consumption before construction is

[22]Note that if the imported water were owned by a competitive agent, the agent would not want to build the project until the price equaled $c_I + v_m + \frac{rF}{I}$ since this agent would not capture the external benefit to the groundwater stock from percolation. Thus the welfare theorems will hold if property rights are assigned such that there are no externalities, i.e., the groundwater and imported water must be owned by the same agent.

[23]For simplicity, this illustration ignores local surface water, L.

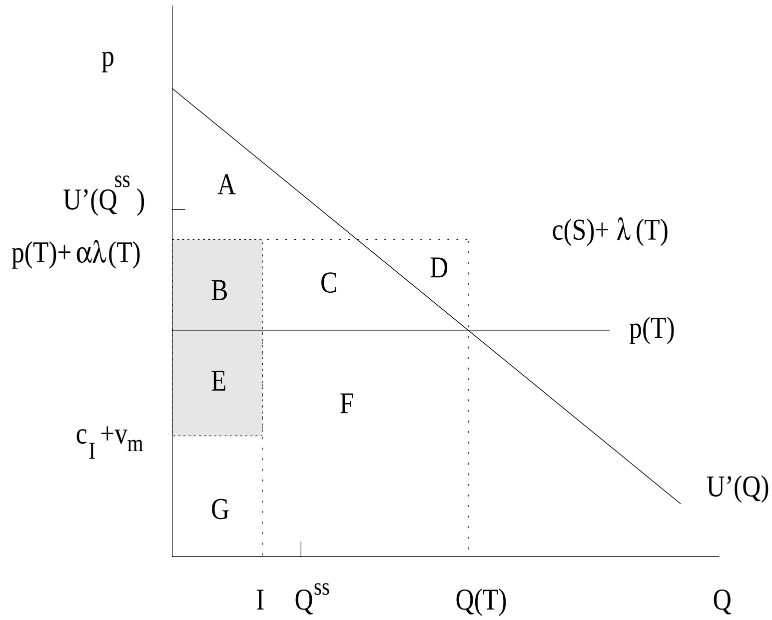

Figure 3: Marginal benefit curve and price when the water-import project is efficiently constructed. The shaded area is the interest payment on the set-up cost rF. Note that at T, the average cost plus the interest payment on the set-up cost exceeds the trigger price $p(T)$ by the percolation benefit $\alpha\lambda(T)$, i.e., $c_I + v_m + \frac{rF}{I} = p(T) + \alpha\lambda(T)$.

$$U(Q^-) + \alpha\lambda(T)Q^- - (c(S) + \lambda(T))q^-$$

$$= \text{Area(A+B+C+E+F+G)+Area(B+C+D)-Area(B+C+D+E+F+G)}$$

$$= \text{Area(A+B+C)}$$

Similarly, the net benefit after construction is Area(A+B+C+B+E). Thus equation (6) shows that Area(B+E)=rF when the project is constructed. Note also that the condition $c_I + v_m + \frac{rF}{I} < U'(Q^{ss})$ ensures that there is residual demand for groundwater after the project is constructed.

3.2 Modeling Inefficiencies in Water Use

The planner's problem allows calculation of the efficient extraction path of groundwater and efficient construction time of the water project. Section 2 describes four main problems associated with water allocation by markets: project subsidization, prohibition of water marketing, common-pool extraction of groundwater, and a ban on groundwater mining. To estimate the deadweight loss from various policies, the model above is adapted to analyze the effects of these distortions on the dynamic water use decisions of agents. The results are then compared to the efficient solution from the planner's problem.

The analysis addresses two project subsidies: a set-up (construction) cost subsidy and an operating cost subsidy. These subsidies distort the optimizing decisions regarding groundwater mining and project construction.[24] A project planner with these subsidized costs would construct the project too early since the trigger price in equation (8) would be reduced by these subsidies.

The prohibition of interstate water marketing is analyzed by noting that if the water cannot be sold, its market value is zero ($v_m = 0$); i.e., the imported water I has zero opportunity cost to the region considering the import project. The effects of the ban on the market are similar to a subsidy on the operating costs of the project. In particular, the steady state is unaffected but the project is constructed too early.

To estimate the welfare loss due to common-pool extraction of groundwater, we follow Gordon (1954) in assuming rent dissipation in each period.[25] With this myopic behavior, extractors pump groundwater until the marginal benefit equals the average pumping cost,

[24]Note that due to the flow constraint, these subsidies do not change consumption on the margin. Thus the direct effect of the subsidies is only through the construction date. In fact, if agents could not choose the construction date and the efficient date were mandated, the extraction paths would be efficient and the subsidies would not lead to a loss of efficiency.

[25]An alternative approach would be to solve the common-pool extraction game for a finite number of pumpers. However, Brooks *et al.* (1999) show that the extraction path from assuming rent dissipation is the same as the path found by taking the limit of Markov perfect equilibria as the number of pumpers increases. Since our model satisfies their conditions and there are many groundwater extractors in Arizona, we follow the simpler approach of assuming rent dissipation.

i.e., equation (2) implies that $U'(Q) = c(S)$ in each period. Thus groundwater is pumped too fast in the common-pool equilibrium. Since pumping costs increase with cumulative overdraft, pumping decreases over time and consumption is smoothed to a steady state. Note that steady-state consumption is independent of the behavioral assumptions of the model and thus is unchanged in the common-pool equilibrium. However, in the efficient steady state, cumulative overdraft does depend on extractors' willingness to forego mining groundwater in order to reduce pumping costs in the steady state. In the common-pool equilibrium, individual extractors cannot capture this future benefit. Therefore, groundwater is pumped until the steady-state marginal benefit equals the marginal pumping cost, i.e., $U'(Q^{sscp}) = c(S^{sscp})$. Comparing this equation with equation (4) shows that too much groundwater is mined in the common-pool equilibrium.

The ban on groundwater mining is analyzed by simply forcing the model to a steady-state after the ban takes effect. The ban creates the incentive to mine groundwater too quickly since there is no payoff to conserving groundwater for extraction after the ban.

4 A Simulation Model of Arizona Water Use

The model developed in Section 3 is parameterized and solved numerically to estimate the deadweight loss under various policy scenarios. Since the solution to the model involves solving several differential (integral) equations, a numerical approximation of a discrete time version of the model is solved.

4.1 Numerical Solution of the Model

The simulation model is solved to find efficient groundwater extraction and project timing. Finding this solution requires several steps. We begin by arbitrarily fixing the project construction date. The price path can then be computed by choosing an initial shadow value and using its equation of motion to define the price path. This price path then defines the consumption and extraction paths. The initial shadow value is then adjusted such that the extraction path pumps groundwater until the cumulative overdraft satisfies the terminal condition in equation (4). Once the correct initial shadow value is found, welfare is computed. This result is then compared to the welfare computed by fixing a different construction date. The construction date that yields the highest welfare is the efficient solution.

Welfare effects of the policies are estimated using a similar approach. The simulation model is solved to find the optimal construction time given the project subsidies and the ban on the interstate market. The deadweight loss is then the difference between efficient welfare and welfare under the policy distortions. The loss from common-pool extraction is estimated by pumping groundwater to the common-pool steady state with complete rent dissipation in every period. The optimal construction time is then computed, and the resulting welfare is compared to welfare from the efficient solution. Finally, the model is adapted to analyze inefficiencies from a ban on groundwater mining in year 2025. In this case, the optimal shadow values are defined by the terminal condition on groundwater mining.

4.2 Model Parameters

To apply the model, a set of parameters is developed for water demand, supply, and aquifer conditions in central Arizona and for the CAP. Here we provide an overview of the data sources and procedures used in developing the parameters. Table 2 reports parameter values, and Appendix 1 describes the procedures in more detail.

Aggregate demand is composed of two linear demand equations: municipal and agricultural. The municipal demand equation shifts at discrete time periods based on actual and projected population growth in the three-county area served by the CAP. The agricultural demand equation remains constant through time and has a lower choke price than municipal demand (Table 2).

Parameters for the CAP include annual deliveries I, construction costs F, operating costs c_I, and market value of CAP water v_m (Table 2). The CAP parameters are developed primarily from data contained in the Bureau of Reclamation's analysis of repayment obligations of CAP beneficiaries (U.S. Department of the Interior 1998). The unsubsidized set-up cost is the present value in 1987 (at the time that CAP service begins) of actual and projected annual CAP construction expenditures between 1972 and 2002. The subsidized set-up cost is the present value in 1987 of projected capital repayments of water users. Unsubsidized operating costs include electricity costs evaluated at a market price and conventional operating and maintenance costs. Subsidized operating costs, in contrast, evaluate electricity costs at an administered price. Finally, the market value of CAP water is the price of water from a simulated interstate market for the Colorado River basin (Booker and Young 1994). This value equals zero in the absence of a market.

The aquifer model developed for central Arizona is consistent with the standard aquifer model used in Gisser (1983) and Feinerman and Knapp (1983). The model is constructed from data reported in hydrological investigations (U.S. Department of the Interior 1986a, 1986b) and collected in planning documents for implementation of the Arizona Groundwater Management Act of 1980. Based on Bush and Martin (1986), the cost of groundwater pumping, $c(S)$, increases linearly with pumping depth in central Arizona. Water is assumed to be distributed uniformly within the region's groundwater reserves.

5 Perspectives on the Value of CAP

This section initially applies the simulation model to estimate the social value of CAP and the value of CAP to Arizona. We next study the value of an alternative site for the project. The simulation model uses initial conditions in the year 1950. All welfare levels are reported as a 1950 present value using 1998 dollars. A sensitivity analysis of several parameters is reported in Appendix 2.[26] It shows that the qualitative results reported here are valid for a wide variety of parameters. However, the numerical results are sensitive to the discount rate, as would be expected.

5.1 The Value of CAP

Four model solutions are considered to shed light on the value of CAP: the efficient solution (labeled the *Efficiency* case); a solution in which CAP is never constructed (the *NoBuild* case); Arizona's preferred solution given the distorted costs of imported water (the *Subsidy* case); and a solution in which CAP is constructed at its actual completion date in 1987 (the *Build=1987* case). The model solves for project timing in the *Efficiency* and *Subsidy* cases,

[26] The sensitivity analysis is based on the framework of Section 5.1.

but takes project timing as given in the *NoBuild* and *Build=1987* cases.

Begin with the efficiency question: Should the CAP be built and, if so, when? If $c_I + v_m + \frac{rF}{I} < U'(Q^{ss})$, the trigger price is less than the steady-state price. Since this inequality holds for the CAP parameters, construction of the project is efficient. Efficient construction timing builds the project in 2058 (T=108) and generates welfare from efficient water use of $61.090 billion. This is the *Efficiency* case in Table 3.

Although CAP construction is efficient, its incremental value is small relative to sole reliance on groundwater and local surface water in central Arizona. If CAP were never constructed, efficient groundwater mining would yield $61.021 billion in welfare. This is the *NoBuild* case (Table 3). CAP's incremental value thus equals $0.069 billion.[27] Two factors explain this small value.[28] First, CAP is a relatively expensive water supply at over $5 billion in construction costs and almost $220/acre-foot in operating costs.[29] Second, CAP augments substantial local, renewable water resources exceeding 1.1 million acre-feet per year. If CAP were never built, groundwater mining would continue deeper into the aquifer, last longer, and mine an additional 624.6 million acre-feet of groundwater. In effect, CAP is not an essential water supply for central Arizona.

Given CAP's low value, what explains the political pressure exerted by Arizona to construct CAP as a Reclamation project? To understand Arizona's perspective, consider the market distortions faced by Arizona: a ban on interstate marketing and subsidized

[27] Without the CAP, efficient groundwater mining continues to a pumping height of 3,592 feet. Since availability of groundwater at this depth is uncertain, we constrained the pumping height to be 2,400 feet in a separate model run. Welfare in this case is $61.020 billion. Thus, pumping to the lower depth contributes little surplus because the marginal value of the water is close to the pumping cost.

[28] The choice of the discount factor also affects this value. As reported in the sensitivity analysis (Appendix 2) a smaller discount factor yields a higher value.

[29] The analysis takes the size of the CAP as exogenous. A project of different size may yield higher welfare. See Holland (1999) for an analysis of endogenous capacity choice in a similar problem setting.

construction and operating costs. Under these conditions in the model, Arizona would have wanted to construct CAP in 1971[30] and would have received a net benefit from consumption and transfers of $61.306 billion(the *Subsidy* case in Table 3).[31] While Arizona gains from these policies, the true costs must still be borne by the economy. These distortions would have produced a deadweight loss of $3.016 billion (4.9% below efficient welfare). In fact, CAP's deadweight loss under these policies would have exceeded its incremental value.

Finally, consider the actual construction date of 1987 (the *Build=1987* case). This yields welfare of $59.767 billion and a deadweight loss of $1.323 billion. Clearly, this date is sub-optimal for both Arizona and the social planner. Delay is obviously desirable from the planner's perspective, as welfare increases by $1.693 billion relative to welfare generated by optimizing Arizona's net benefit. In contrast, delay reduces Arizona's net benefit by $0.177 billion. As above, the deadweight loss from construction in 1987 was greater than the incremental value of CAP. Ironically, building CAP in 1987 was worse than never building CAP at all.

Figures 4, 5, and 6 show the groundwater pumping height, water price, and groundwater pumping paths through 150 years for these four cases of CAP timing (*Efficiency*, *NoBuild*, *Subsidy*, and *Build=1987*).[32] The price paths and pumping height paths are continuous, as would be expected, but the pumping height is kinked when CAP is constructed in the various cases.[33] The groundwater pumping paths follow a sawtooth pattern purely as

[30]This date is a reasonable reflection of Arizona's perspective. CAP was initially introduced into Congress in 1947. This would have implied a completion date in the late 1960's if the project had not been delayed by litigation over the Colorado River Compact.

[31]From the Arizona perspective, the best scenario would be to receive the federal subsidies and, in addition, to be allowed to market the CAP water. In this case, Arizona would receive an additional transfer from selling the water prior to construction of the project. Under these conditions, Arizona would want CAP built in 1985 and would receive a net benefit of $62.136 billion.

[32]Although we graph outcomes through 150 years, steady states are reached after 700 years in these cases.

[33]The efficient price grows over time, from $p(0)$=$99.90 to $p(T)$=$348.25 to $p(T^{ss})$=$537.92. Note that

an artifact of the modeling simplification that defines seven discrete shifts in water demand (Figure 6). Annual pumping declines within a period of stable demand (e.g., between years 0 and 10), then increases discontinuously as the next period of (higher) demand begins. After population stabilizes in t=75, pumping decreases until reaching a steady state. The intertemporal decline in pumping follows from the standard Hotelling result and the increase in pumping cost with cumulative overdraft. Note also that groundwater pumping shifts down by approximately 1.3 million acre-feet (CAP capacity) when CAP is constructed at the various times in the different cases. This is the pattern depicted for the theoretical model in Figure 2.

Three features of the figures illustrate the findings on the welfare effects across the four cases. One, in the initial stage of extraction, the groundwater extraction path when CAP is not built (*NoBuild*) is virtually indistinguishable from efficient groundwater extraction (*Efficiency*). The two cases begin to diverge after about 75 years, but then diverge markedly after CAP is constructed in T=108 in the *Efficiency* case. Ultimately, the pumping height and price are much higher in the *NoBuild* case because it reaches a different steady state. Although the *NoBuild* case eventually differs substantially from the efficient allocation, the significant differences in the outcomes are discounted by at least 75 years and thus are quite small. This illustrates our welfare finding that efficient construction of CAP had a small incremental value relative to not constructing CAP.

Two, the efficient path mines significantly more groundwater between 1987 and 2058 than the cases in which CAP is built in 1971 or 1987 (the cases *Subsidy* and *Build=1987*). What then is the source of the deadweight loss in these inefficient cases? Since the efficient

as in equation 3, the growth rate of the efficient price is less than the interest rate.

price path is everywhere higher than the price path in these two cases, it would seem that these cases do not conserve enough groundwater. In fact, this price relationship holds before CAP is constructed when too much groundwater is pumped and overdraft is excessive. After CAP construction, however, these two cases substitute expensive CAP water for the cheaper groundwater. In this stage, too little groundwater is mined and the pumping height is too low. After 2058, then, these cases again pump too much groundwater. Because the steady state is identical in all these cases, the pumping heights, prices and pumping will be equal. This illustrates that the large deadweight losses of these cases do not come from mining too much or too little groundwater *per se*, but rather from the early substitution of expensive imported water for the cheaper groundwater.

Three, comparing allocations when CAP is built in 1971 (*Subsidy*) rather than 1987 (*Build=1987*) shows that, again, the increased inefficiency stems from importing expensive surface water too early (Figure 6). The paths differ substantially only between 1971 and 1987, but otherwise are quite similar. Despite this similarity, the deadweight loss decreases by $1.693 billion (over fifty percent) with the later construction date. This minor difference in allocations thus translates into a major welfare difference.

5.2 The Political Economy of Project Siting: Trading Off Construction and Operating Costs

Winning congressional approval was a critical hurdle in development of individual Reclamation projects. In an early decision on CAP, state leaders in Arizona and Bureau of Reclamation officials made a political calculation about the U.S. Congress when choosing between competing proposals for siting the aqueduct to central Arizona (Ingram, Martin, and Laney 1982). One proposed route diverted water from the Colorado River in northern Arizona. The northern route had relatively high construction costs (it required several long tunnels) and low operating costs (the diverted water would flow downhill by gravity to central Arizona). The second proposed route diverted water farther downstream in western Arizona. The western route had relatively low construction costs (no tunnels) and high operating costs (the water would be pumped vertically more than 1,000 feet to divert it from the river). With significantly lower construction costs, the western route "was finally settled upon by state leaders and the Bureau officials as more likely to be approved by Congress" (Ingram, Martin, and Laney 1982, p. 152). In the political calculus, lump-sum construction costs appeared to register more heavily than recurrent operating costs.

Which route creates the most value? The western route has construction costs of \$5.059 billion and operating costs of \$219.38 per acre-foot (Table 2). As noted above, the optimal solution to this problem generates welfare of \$61.090 billion. The proposed northern route, in contrast, has construction costs of \$8.009 billion and operating costs of \$113.70 per acre-foot.[34] The optimal programme under these conditions generates greater welfare, \$61.151 billion. Thus, the political calculation that ultimately resulted in construction of the western route reduced the potential value of CAP.[35]

[34]A 1947 Reclamation study finds that construction costs for the northern route are \$400 million higher than the western route (Ingram, Martin, and Laney 1982). After converting to 1998 dollars, we arrive at the figure of \$8.009 billion for the northern route's construction costs. The operating costs for the northern route are computed by subtracting the energy costs for pumping water along the western route, except those costs of pumping water from Phoenix to Tucson, which would exist with either route. We should note that, in contrast to the parameters used for the western route, the numbers applied for the northern route are from secondary rather than primary sources.

[35]This conclusion ignores the potential environmental costs of the northern route. This route would require a diversion dam at Bridge Canyon in the lower Grand Canyon region. The decision to vacate the northern route came in the late 1940's. In the 1960's, the Bureau of Reclamation proposed the Bridge Canyon site for one of two hydroelectric dams in the upper and lower Grand Canyon region. This spawned vociferous opposition from the nascent environmental community in the United States, which ultimately led Reclamation to withdraw the proposed dams. This was an important chapter in contemporary environ-

6 A Political Exchange: CAP Subsidies for Reform of Groundwater Law

A primary political motivation for the construction of CAP was to reduce and, ultimately, eliminate groundwater mining. Federal policy makers knew, however, that CAP alone would not correct Arizona's perceived groundwater problem. Thus, the obligation to reform Arizona groundwater law in exchange for CAP was written explicitly into the federal law authorizing CAP (Sax, Abrams, and Thompson 1991). When Arizona wavered on this provision, Interior Secretary Andrus was dispatched to enforce the law.[36] The federal government had already financed California's vast Central Valley Project to "rescue" farmers from groundwater overdraft (Reisner 1986). The government needed to enforce the law to establish credibility on its coupling of state groundwater reform and federal imported surface water. The Arizona Groundwater Management Act of 1980 was the result. It includes two major features: development of well-defined groundwater rights in place of common-property rights and a ban on groundwater mining beginning 2025.

6.1 Well-defined Groundwater Property Rights

The prospective political exchange of CAP subsidies for groundwater reform forced Arizona to compare two possible outcomes: (1) building CAP in 1987 with groundwater rights defined under a new law, versus (2) building CAP without subsidy but with groundwater rights

mental history: "The battle over the Grand Canyon dams was the conservation movement's coming of age" (Reisner 1986, p. 295).

[36]Sax, Abrams, and Thompson (1991, p. 494) write, "At this point in late 1979 ...the Carter Administration turned the thumbscrews. Cecil Andrus, the Secretary of Interior, explicitly stated that he would allocate no Central Arizona Project water to the state unless there was a vigorous groundwater management act in place."

defined as common property.[37] The former outcome is the *Build=1987* case of Section 5; the latter outcome is labeled *ComProp.* Arizona's optimal construction timing for CAP would be 2041 under the conditions of *ComProp.* This date is earlier than efficient timing because of myopic pumping, yet much later than the subsidized construction in 1987. Arizona clearly prefers *Build=1987* in light of the government subsidies; the net benefit to Arizona is $1.027 billion higher under *Build=1987* than *ComProp* (Table 4). Figure 7 shows the groundwater pumping height paths for the two outcomes. The myopic pumping of *ComProp* results in significantly greater pumping height and overdraft relative to *Build=1987*.[38]

Was the political exchange—subsidies for legal reform—sound economic policy? Comparison of deadweight loss suggests not. The loss of *Build=1987* is $1.323 billion; the loss of *ComProp* is $0.988 billion.[39] The water-project subsidies introduced a larger inefficiency than was removed by the property-rights reform.[40]

A narrower perspective on the political exchange relates to the federal government's 1979 decision to enforce the federal requirement for state groundwater reform. If we take the 1987 construction date as given, what are the consequences of federal enforcement? Without enforcement, common-pool depletion of groundwater and CAP construction in 1987 (labeled

[37] Arizona's construction of CAP without federal subsidy was a realistic alternative. According to Ingram, Martin, and Laney (1982, p. 152), "...the major source of the controversy in Arizona over the project at this time was between those who believed the state should go it alone in building the project and those who believed it could only be done with federal assistance. Those holding the latter view prevailed, and the pattern of bargaining with the federal government began in 1947."

[38] As discussed in Section 3, the steady-state pumping height is lower for the efficient case relative to the common-property case since myopic pumpers do not consider the effect of current pumping on the steady-state pumping cost. According to the model, the efficient steady-state height is 1538 feet while the common-property steady-state height is 1611 feet.

[39] The deadweight loss under *ComProp* is 1.6% of welfare. Research on New Mexico and Texas aquifers found the value of groundwater management to be less than 1% of welfare (Gisser 1983; Kim et al. 1989). Feinerman and Knapp (1983) found a value to management of 12% in a California aquifer.

[40] Note that the monitoring cost of enforcing well-defined groundwater rights is not considered. Adding these costs would increase the deadweight loss of the *Build=1987* case with well-defined groundwater rights.

ComPrp87) result in a deadweight loss of \$2.096 billion (Table 4). With enforcement, well-defined groundwater rights and CAP construction in 1987 result in a deadweight loss of \$1.323 billion. Thus, a substantial return to the well-defined groundwater rights, \$0.773 billion, accrues because of the federal government's enforcement.[41] From this perspective, the federal government avoided a worse outcome of subsidizing, building in 1987, and not enforcing the requirement for reform.

6.2 The Ban on Groundwater Mining After 2025

The ban on groundwater mining is scheduled to begin January 1, 2025. The ban would force groundwater pumping to a steady state centuries before a steady state would be reached if pumpers were allowed to pump freely (either with well-defined or common-property rights) (Figure 7). The ban in 2025 (denoted *Ban=2025*) is assessed while fixing the CAP construction date at 1987 and extracting groundwater with well-defined property rights. Over 308 million acre-feet of groundwater that are pumped without the ban remain in the aquifer with the ban. Imposing such a constraint is clearly harmful: the ban results in a deadweight loss of \$2.515 billion (Table 4).

Note that groundwater pumping prior to 2025 increases in response to the ban.[42] Beginning from the initial date, groundwater pumping with the 2025 ban exceeds pumping without the ban (i.e., with well-defined groundwater rights, CAP construction in 1987, and no ban). The difference grows over time until, by the early 2020's, roughly 3.25 million

[41] In effect, the federal government acted as an agent for Arizona's citizens by prodding the state government into the groundwater reform.

[42] This empirical finding is consistent with Long's (1975) theoretical result on nonrenewable resource extraction in the case of nationalization of the resource. He shows that the resource will be extracted at a faster rate given nationalization of the resource at a known future date relative to the case of no possibility of nationalization. Lee (1978) derives a similar result for the case of a price ceiling for a nonrenewable resource that is binding in the future.

acre-feet is pumped under the ban compared to roughly 2.75 million acre-feet without the ban. The relative pumping rates result in pumping heights in 2025 of almost 525 feet under the ban and roughly 475 feet without the ban (*Ban=2025* versus *Build=1987* in Figure 7). Thus, the ban produces two effects: too little groundwater pumping after the ban and too much pumping before the ban.

Two factors—the relatively large deadweight loss and the prospect of distributing the ban's artificial scarcity—raise doubts about the ban's credibility. The deadweight loss of $2.515 billion is substantially larger than the deadweight loss from the comparable case, *Build=1987*, with its deadweight loss of $1.323 billion. Moreover, groundwater pumping would decrease abruptly after the ban, with a reduction of almost 2.3 million acre-feet in 2025. How would this artificial scarcity be distributed? It is unclear. Given these factors, economic pressure to remove or delay the ban should increase steadily as 2025 approaches.

7 Conclusion

In *Cadillac Desert*, Reisner's central thesis is that water project development in the American West was financially extravagant and wasteful of water resources. Reisner presents ample anecdotal and historical evidence to support his thesis. In this paper, we develop a model of the dynamic tradeoff between water project construction and groundwater mining that incorporates a project's set-up costs and capacity constraint. We find powerful support for Reisner's central thesis by applying the model to Arizona's water problem. First, CAP should have been built in 2058, over seven decades later than the actual construction date. Second, we find a relatively small increment to social surplus from constructing CAP: $69 million. This small increment is explained by the fact that groundwater is relatively plentiful and the CAP is quite expensive. Third, the deadweight loss from constructing CAP in 1987 was quite large: $1.323 billion. We reach a stark conclusion: building CAP in 1987 was worse than never building CAP at all.

As with all subsidized Reclamation projects, Arizona's perspective on CAP involved a comparison of federal subsidy versus deadweight loss. Arizona could have implemented the efficient program of groundwater mining and CAP timing. Instead, it opted for the federal cost subsidies—even though their distortions would have yielded the deadweight loss of $3.016 billion—because the project costs borne by the federal government exceeded the deadweight loss by $0.216 billion. In the end, delaying CAP's construction to 1987 significantly reduced the value of the federal subsidy to Arizona.

With CAP, the federal government introduced a new strategy of trading a subsidized project for state groundwater reform. This strategy produced bad policy in the Arizona case. We estimate that common-pool extraction yields a deadweight loss of $0.988 billion. Because CAP subsidies create a greater inefficiency, trading CAP subsidies for groundwater reform resulted in a net cost of $335 million. This comparison provides important perspective on future federal policy. A federal commission, the Western Water Policy Review Advisory Commission, recently recommended that the exchange of federal project subsidy for state groundwater reform be adopted as general federal policy.[43] A better recommendation, arguably, is that water-import projects simply should not be subsidized.[44]

While the analysis focuses on water-resource development in the western United

[43]The Commission wrote, "The Congress should require state management of groundwater and regulations of withdrawals as a condition of federal financial assistance for construction of new water storage projects" (Western Water Policy Review Advisory Commission 1998, p. 6-23).

[44]Due to the percolation externality (a fraction of imported water percolates into the local aquifer), a Pigouvian subsidy of water-import projects may be warranted. The efficient subsidy would almost certainly be lower than the existing CAP subsidies. This topic is beyond the scope of the current research.

States, the methodology has application in other regions and time frames. An ambitious proposal in China, for example, would import water to northern China from the Yangtze River basin in southern China (Postel 1999). The project, estimated to cost $30 billion, would provide water in part to substitute for nonrenewable groundwater reserves in the north. Within the United States, global warming could increase water demand. Mendelsohn, Nordhaus, and Shaw (1994) suggest that irrigated agriculture may increase in the West and South sometime after 2050. More refined climate models forecast that large regions of the United States may be hotter and drier, not hotter and wetter, thereby suggesting that water demand may increase substantially in that time frame (Lewandrowski and Schimmelpfennig 1999).[45] Global warming, consequently, could trigger a second prolonged period of water-resource development in the 21st century.

[45] In a review of three studies, Lewandrowski and Schimmelpfennig (1999, p. 49) conclude that "all indicate large increases in irrigation [in the United States] under climate change."

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Appendix 1: Data Sources and Procedures Underlying the Model Parameters

The appendix documents the sources of data and procedures applied in developing the parameters. Table 2 of the main text summarizes the model parameters. All monetary parameters are reported in 1998 dollars.

(1) Aggregate water demand in Central Arizona.

Water demand is composed of two sectors: municipal and industrial (M&I) demand and agricultural demand. Linear demand equations for each sector are constructed from estimates of the price elasticity of demand and data on water prices and quantities. Aggregate water demand sums the two individual sectoral demands. The study area encompasses the three-county region of central Arizona served by the CAP.

M&I water demand. The M&I demand function shifts intertemporally based on population levels. M&I water demand in 1980 serves as the baseline. Two steps are taken to construct the 1980 demand equation. First, a 1980 demand equation is developed for Tucson using data from Agthe, et al. (1986), Agthe and Billings (1981), and ADWR, Tucson Active Management Area (1984). Second, the slope of Tucson's demand equation is adjusted based on the ratio of total population in the three counties to population in Tucson. The resulting M&I demand equation for central Arizona in 1980 is

$$q = -780.89p + 1400861$$

where q is in acre-feet and p is in \$/acre-foot. The choke price for M&I demand is \$1,793.93.

Intertemporal M&I water demand is adjusted based on actual or projected population levels in the region. We define seven periods in the analysis: 1950-59; 1960-69; 1970-79; 1980-89; 1990-99; 2000-24; and 2025-infinity. Annual M&I demand is constant within a period, yet shifts discretely across periods to reflect population changes. By assumption, the region's population is modeled as stable after 2025. Population data are from ADWR, Phoenix Active Management Area (1984, 1991); ADWR, Pinal Active Management Area (1985); ADWR, Tucson Active Management Area (1984, 1996); and U.S. Department of Commerce, U.S. Bureau of the Census (1952, 1973).

Agricultural water demand. To obtain a price elasticity of demand for agricultural water, a water demand function is estimated from cross-sectional microdata on farms in this region of Arizona. The data are from the 1984 Farm and Ranch Irrigation Survey (U.S. Department of Commerce, Bureau of the Census 1986). Evaluated at the mean, the elasticity is -0.178. Total agricultural water demand is then constructed using the price elasticity; the mean price (groundwater pumping cost); and total agricultural water use in 1980 (ADWR, Phoenix Active Management Area 1984; ADWR, Pinal Active Management Area 1985; ADWR, Tucson Active Management Area 1984); and the mean price. The annual agricultural demand equation for central Arizona is

$$q = -9108.90p + 4565925$$

where q is in acre-feet and p is in \$/acre-foot. The choke price equals \$501.26/acre-foot. Agricultural demand is modeled as constant over time.

(2) Central Arizona Project.

Annual CAP delivery. The annual CAP delivery of 1,287,000 acre-feet is the mean of the projected deliveries for the period 1998-2046 (U.S. Department of the Interior 1998). A sensitivity analysis is completed using an annual delivery of 1,144,100 acre-feet. The latter number is used in Booker and Young (1994).

Construction costs. The unsubsidized set-up cost (\$5,058,802,600 at a 3.21% discount rate) is the present value of actual and projected CAP construction expenditures from 1972-2002 (U.S. Department of the Interior 1998, p. 36). The figure also includes capital expenditures by retail water districts on distribution systems from the CAP aqueduct to the districts (Wilson 1992). Present value is computed for 1987, the year at which CAP was completed to the Phoenix metropolitan area.

Construction cost subsidies. Subsidized set-up cost (\$2,443,567,540 at a 3.21% discount rate) consists of the legally required repayment of CAP construction expenditures (U.S. Department of the Interior 1998). Computations of subsidized set-up costs also incorporate interest-free loans made to retail water districts for distribution systems that transport water from CAP (Wilson 1992). Present value is computed for 1987.

Operating costs. Unsubsidized operating cost equals $219.38. This number has three components. First, it includes an unsubsidized electricity cost for pumping water through the CAP system of $130.74/acre-foot. This figure is computed using a retail market price for electricity in the western United States (Congressional Budget Office 1997). Second, it includes observed CAP operating costs (other than those related to electricity) of $52.42/acre-foot (U.S. Department of the Interior 1998). Third, it includes projected operating costs of transporting water from the CAP aqueduct to retail water consumers of $36.22/acre-foot (Bush and Martin 1986).

We also conduct a sensitivity analysis on the electricity cost of pumping CAP water. Using a higher price for electricity in the region (Booker and Young 1994), this cost equals $186.68/acre-foot (instead of $130.74/acre-foot).

Operating cost subsidies. Subsidized operating cost for CAP water equals $98.45/acre-foot. Two adjustments are made to unsubsidized operating cost to compute subsidized operating cost. The adjustments are made to an electricity charge and to a charge for other operating costs. Both adjustments involve charges levied on CAP customers by the Central Arizona Water Conservation District (Central Arizona Project 1999).

Opportunity cost of CAP water. Two levels of opportunity cost for CAP water are applied: zero and $36.89/acre-foot. The latter number is the market-clearing price from a simulated Colorado River market (Booker and Young 1994). In contrast, without an interstate water market in the Colorado River basin, Arizona faces a zero opportunity cost for CAP water. The Colorado River market price also incorporates a water transport loss factor to convert from an in-river price to a central Arizona price. CAP transport losses for 1994-98 equal 4.76%.

(3) Central Arizona aquifer model

Parameters for the central Arizona aquifer model are developed from research publications of the U.S. Geological Survey and central Arizona planning documents (ADWR, Phoenix Active Management Area 1984, 1991; ADWR, Pinal Active Management Area 1985; ADWR, Tucson Active Management Area 1984, 1996).

Aquifer parameters. Three parameters characterize the aquifer model commonly applied in economic research (e.g., Gisser 1983; Feinerman and Knapp 1983; Kim, et al. 1989). One, the land area overlying the aquifer defines the two-dimensional horizontal area of the underground reservoir. Two, the specific yield of the aquifer is the fractional content of water in the aquifer's three-dimensional space. Three, the pumping depth in a given year defines the initial condition of the aquifer. These three parameters for Central Arizona are, respectively: 5,529,139 acres overlying the aquifer; a specific yield of 0.055 feet of water per vertical foot of the aquifer; and a pumping depth of 88.0 feet in 1950. Additional description of the procedures applied is available upon request from the authors.

Two comments pertain to the aquifer model. First, the model assumes that the water table remains uniform within the aquifer independently of the spatial location of pumping. This is the conventional assumption in the economics literature. Second, hydrological evidence indicates that the aquifer depth, or thickness, exceeds 2,000 feet in many sub-basins within central Arizona (ADWR 1994). In the analysis, consequently, the model reaches a steady-state pumping depth instead of culminating in physical exhaustion of the aquifer.

Natural recharge rate. Groundwater recharge in central Arizona occurs naturally at the rate of 126,000 acre-feet per year, as reported in the central Arizona planning documents. The conventional assumption, that recharge occurs without a time lag, is applied.

Return-flow recharge coefficient. In addition to natural recharge, a share of water applied above ground percolates into the aquifer. Based on information in the central Arizona planning documents, the return-flow recharge coefficient equals 0.257.

Groundwater pumping cost. Groundwater depletion costs depend on energy costs for water pumping; maintenance costs; and well construction costs. Based on Bush and Martin (1986), the cost of pumping one acre-foot of groundwater one vertical foot is $0.33389. Pumping cost is linear in pumping depth and thus increases as the aquifer is depleted.

(4) Local surface water supply

Average surface water supply by the local rivers of central Arizona equals 984,000 per year (ADWR, Phoenix Active Management Area 1984, 1991; ADWR, Pinal Active Management Area 1985; ADWR, Tucson Active Management Area 1984, 1996). This water is supplied at a cost of $36.22/acre-foot, which is the 1980 price charged by the Salt River

Project in central Arizona (Regli 1985).

(5) Interest rate

The analysis applies an interest/discount rate of 3.21%. The rate of 3.21% is the average real rate for 1972-1997. To find the average, annual rates are first computed as the difference between the 30-year Treasury bond rate and inflation rate (Executive Office of the President, Council of Economic Advisors 1999). The interest rate serves two functions: (1) to compute present value net benefit in the dynamic model and (2) for compounding and discounting of annual construction expenditures to obtain CAP set-up costs.

Appendix 2: Sensitivity Analysis

This appendix reports the sensitivity of the numerical results in Section 5.1 to variations in the discount rate, CAP operating cost, and CAP delivery quantity. As one would expect, the numerical results are quite sensitive to the interest rate. The efficient welfare calculation decreases by over $50 billion when the interest rate increases from 2.21% to 4.21%. Efficient CAP timing also changes substantially, by over 50 years. However, the interest-rate sensitivity follows predictable patterns. For example, total welfare decreases in the interest rate because a higher rate puts less weight on the infinite stream of benefits from the renewable surface water. Furthermore, CAP is constructed later as the interest rate increases because a higher interest rate implies a higher trigger price: $c_I + v_m + \frac{rF}{I} - \alpha\lambda(T)$. Note also that the deadweight losses (both in dollars and in percentages) of the *NoBuild* and *Subsidy* scenarios decrease in the interest rate.[46]

Although the numerical results are sensitive to interest rate variation, the qualitative results remain consistent across the different rates. For example, even with a relatively low real interest rate of 2.21%, the CAP should not have been built until the year 2031. Thus, the efficient time to build CAP was certainly much later than its actual construction date.

[46] That the deadweight loss from the *Build=87* scenario is not monotonic in the interest rate is not surprising. For example, in the case of constructing CAP in 2058 (T=108), the deadweight loss is zero when the interest rate is 3.21% but is positive for lower and higher interest rates.

In addition, the deadweight loss from constructing CAP in 1987 is greater than the loss would have been if CAP were never constructed. With interest rate variation, the optimal construction time from Arizona's perspective varies from 1951 to 1982 (the *Subsidy* case). This is a plausible range of values since this was the period of time during which the majority of the debate about CAP took place.

As a further test of the consistency of the model, Appendix Table 2 presents the results under the higher energy cost estimate and lower annual CAP deliveries used by Booker and Young (1994) (B&Y). With their parameters, the operating cost is $275.32 (instead of $219.38) and the CAP deliveries are 1,144,000 acre-feet (instead of 1,287,000 acre-feet). (Note that the first column of Appendix Table 2 repeats the baseline case shown in the main text.) The second column incorporates the higher energy cost of CAP deliveries. Since this increases the trigger price and the deadweight loss in each period in which the CAP is built too early, the higher energy cost delays the efficient construction date and increases the total deadweight losses if CAP is built. The smaller CAP deliveries, (columns 3 & 4), decrease steady-state water consumption and welfare. Because smaller deliveries also increase the trigger price, the CAP is constructed later when deliveries are smaller.

Welfare does not change significantly across the variations presented in Appendix Table 2. This follows because the initial shadow values are all quite similar—approximately $34—so the first 108 years of water use is approximately the same across the variations. Thus, welfare differences are heavily discounted. Since welfare and timing are quantitatively consistent across these variations, the qualitative results are also quite robust to these variations. In particular, CAP was constructed far too early, and the loss from constructing CAP in 1987 was greater than the loss would have been if CAP were never constructed.

Table 1: **Governance of Water Resources in the American West: Public Policies and Legal Doctrines**

General Category	**Specific Case**	**Major Features**
Federal Reclamation policy	Central Arizona Project	*Subsidy policy.* Construction costs: interest-free financing and cross-subsidy from power production at dams. Operating costs: cross-subsidy from ad valorem taxes and power production.
Interstate water law	Colorado River Compact	*Quotas with autarky.* Quantity-based apportionment among states in a river basin. Legal impediments to interstate water marketing.
State groundwater law	Arizona Groundwater Management Act	*Extraction from common-pool aquifers.* Individual states may restrict entry, establish quotas, and/or allow groundwater marketing. Arizona law prohibits groundwater mining after the year 2025.

Table 2: **Model Parameters**

Initial conditions: 1950.
All dollar figures in 1998$.

(1) Aggregate water demand. Characteristics: (a) quantity unit is acre-feet per year; price unit is $ per acre-foot; (b) composed of municipal and industrial (M&I) demand and agricultural demand; (c) water demand shifts at discrete time periods based on actual and projected population growth in central Arizona; (d) a kink in demand occurs at the choke price for the agricultural sector.

Period: 1950-1959

$$D(p) = \begin{cases} -196.04p + 351689 & \text{when } p \in [501.26, 1793.93] \\ -9304.78p + 4917623 & \text{when } p \in [0, 501.26] \end{cases}$$

Period: 1960-1969

$$D(p) = \begin{cases} -376.71p + 675795 & \text{when } p \in [501.26, 1793.93] \\ -9485.45p + 5241720 & \text{when } p \in [0, 501.26] \end{cases}$$

Period: 1970-1979

$$D(p) = \begin{cases} -528.50p + 948084 & \text{when } p \in [501.26, 1793.93] \\ -9637.21p + 5514009 & \text{when } p \in [0, 501.26] \end{cases}$$

Period: 1980-1989

$$D(p) = \begin{cases} -780.89p + 1400861 & \text{when } p \in [501.26, 1793.93] \\ -9889.62p + 5966786 & \text{when } p \in [0, 501.26] \end{cases}$$

Period: 1990-1999

$$D(p) = \begin{cases} -1137.51p + 2040620 & \text{when } p \in [501.26, 1793.93] \\ -10246.20p + 6606545 & \text{when } p \in [0, 501.26] \end{cases}$$

Period: 2000-2024

$$D(p) = \begin{cases} -1587.67p + 2848174 & \text{when } p \in [501.26, 1793.93] \\ -10696.40p + 7414099 & \text{when } p \in [0, 501.26] \end{cases}$$

Period: 2025-infinity

$$D(p) = \begin{cases} -2568.53p + 4607754 & \text{when } p \in [501.26, 1793.93] \\ -11677.20p + 9173679 & \text{when } p \in [0, 501.26] \end{cases}$$

Table 2: **Model Parameters** *(continued)*

(2) Central Arizona Project	
(a) annual deliveries (I):	1,287,000 acre-feet.
(b) construction costs (F)	
(i) unsubsidized:	\$5,058,802,600.
(ii) subsidized:	\$2,443,567,540.
(c) operating costs (c_I)	
(i) unsubsidized:	\$219.38 per acre-foot.
(ii) subsidized:	\$ 98.45 per acre-foot.
(d) market value of I (v_m)	
(i) with interstate market:	\$36.89 per acre-foot.
(ii) no interstate market:	\$ 0.00 per acre-foot.
(3) Central Arizona aquifer model.	
(a) aquifer parameters.	
(i) area overlying aquifer:	5,529,139 acres.
(ii) specific yield (saturation rate):	0.055 feet of water per foot of lift.
(iii) pumping depth, 1950:	88.0 feet.
(b) natural recharge rate (R):	126,000 acre-feet per year.
(c) return-flow recharge coefficient (α):	0.257.
(d) long-run pumping cost:	\$0.33389 per acre-foot per foot of lift.
(4) Local surface-water supply.	
(a) deliveries (L):	984,000 acre-feet per year.
(b) cost (c_L):	\$36.22 per acre-foot.
(5) Interest rate (r):	3.21%

Table 3: **The Value of CAP**

CAP Construction Alternative	Subsidy	T	Welfare	Deadweight Loss	Net Benefit to Arizona
Efficiency Case	No	108	$61.090 bill	—	$61.090 bill
NoBuild Case	No	n.a.	$61.021 bill	$0.069 bill	$61.021 bill
Subsidy Case	Yes	21	$58.074 bill	$3.016 bill	$61.306 bill
Build=87 Case	Yes	37	$59.767 bill	$1.323 bill	$61.129 bill

Notes: "n.a." means "not applicable" because CAP is not constructed in this simulation. The *NoBuild* case constrains the planner not to construct CAP. The *Subsidy* case optimizes benefits to Arizona given the subsidized CAP costs, and the ban on interstate water marketing. The *Build=87* case constrains the planner to construct CAP in 1987.

Table 4: **Political Exchange: CAP Subsidies for Reform of Groundwater Law**

Policy Alternative	T	Welfare	Deadweight Loss	Net Benefit to Arizona
Build=87 Case	37	\$59.767 bill	\$1.323 bill	\$61.129 bill
ComProp Case	91	\$60.102 bill	\$0.988 bill	\$60.102 bill
ComPrp87 Case	37	\$58.994 bill	\$2.096 bill	\$60.356 bill
Ban=2025 Case	37	\$58.575 bill	\$2.515 bill	\$59.937 bill

Notes: The *Build=87* case constrains CAP construction to 1987, subsidizes CAP costs, and includes well-defined groundwater rights. The *ComProp* case includes true costs for CAP and common-property groundwater rights. The *ComPrp87* case constrains CAP construction to 1987 and includes common-property groundwater rights. The *Ban=2025* case constrains CAP construction to 1987, includes well-defined groundwater rights, and imposes a ban on groundwater mining in 2025.

Appendix Table 1: **Sensitivity Analysis with Interest Rate Variation**

	r=2.21	r=3.21	r=4.21
Efficiency	T=81 W=$98.961 bill	T=108 W=$61.090 bill	T=131 W=$43.230 bill
NoBuild	T=*n.a.* DWL=$0.734 bill	T=*n.a.* DWL=$0.069 bill	T=*n.a.* DWL=$0.006 bill
Subsidy	T=1 DWL=$6.003 bill	T=21 DWL=$3.016 bill	T=32 DWL=$1.556 bill
Build=87	T=37 DWL=$1.017 bill	T=37 DWL=$1.323 bill	T=37 DWL=$1.172 bill

Notes: "W" denotes welfare. "DWL" denotes deadweight loss.

Appendix Table 2: **Sensitivity Analysis with CAP Delivery and Operating Cost Variation**

	c_I=CBO $\bar{I}$=1287kaf	c_I=B&Y $\bar{I}$=1287kaf	c_I=CBO $\bar{I}$=1144kaf	c_I=B&Y $\bar{I}$=1144kaf
Efficiency	T=108 W=$61.090 bill	T=141 W=$61.042 bill	T=112 W=$60.903 bill	T=146 W=$60.868 bill
NoBuild	T=*n.a.* DWL=$0.069 bill	T=*n.a.* DWL=$0.021 bill	T=*n.a.* DWL=$0.046 bill	T=*n.a.* DWL=$0.011 bill
Subsidy	T=21 DWL=$3.016 bill	T=21 DWL=$4.160 bill	T=22 DWL=$2.767 bill	T=22 DWL=$3.759 bill
Build=87	T=37 DWL=$1.323 bill	T=37 DWL=$1.994 bill	T=37 DWL=$1.309 bill	T=37 DWL=$1.913 bill

Notes: CAP operating cost c_I differs according to use of a CBO electricity price (c_I = \$219.38) or a Booker and Young electricity price (c_I = \$275.32). "W" denotes welfare. "DWL" denotes deadweight loss.