Cadillac Desert Revisited: Property Rights, Public Policy, and Water-Resource Depletion in the American West

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Abstract

Imperfect property rights and government subsidies are pervasive sources of inefficiency in water resource development in the American West. To alleviate central Arizona's dependence on 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 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.

Marc Reisner, *Cadillac Desert: The American West and Its Disappearing Water*, 1986

1 Introduction

Western water law and policy distort incentives for efficient water use in two ways. First, property rights to water resources are imperfectly defined due to uncertain tenure and limited transferability. The prior appropriation doctrine for establishing property rights defines a rule-of-capture for both surface water and groundwater. Market exchanges of water rights are rare within most states and virtually nonexistent across state boundaries. Second, subsidy policy exacerbates the inefficiencies of water law. The federal Reclamation program heavily subsidized the capital investment of western water projects throughout the 20th century in an effort to settle the arid western lands. In this paper, we develop a comprehensive framework to analyze these inefficiencies of western water development and apply the framework empirically to a quintessential case: the Central Arizona Project.

Three lines of research address the distortions that permeate western water law and policy. One, with surface water, Burness and Quirk (1979, 1980) demonstrate that the water-allocation queue defined by state water law promotes inefficient water development and use. Many empirical studies estimate the gains from trade that could occur with lower barriers to voluntary transfer of surface water rights (e.g., Booker and Young 1994; Frederick 1986; Vaux and Howitt 1984; Wahl 1989). Two, with groundwater, agents undertake an inefficiently rapid pace of mining when a rule-of-capture determines groundwater rights (Brown 1974; Hirshleifer, DeHaven, and Milliman 1960). Several studies estimate the benefit of groundwater management using dynamic simulations of common-property depletion (e.g., Feinerman and Knapp 1983; Gisser 1983; Kim, et al. 1989). Three, Reclamation's sizable capital subsidy distorts investments in river development (e.g., Bain, Caves, and Margolis 1966; Eckstein 1958; Hirshleifer, DeHaven, and Milliman 1960).[1] In particular, Freeman (1966) finds that costs outweighed benefits for many Reclamation projects, especially in the latter half of the 20th century.[2] While these three lines of research find significant inefficiencies, they cannot address the combined effects of the various distortions.

This paper studies the interrelated effects of the major western water laws and policies. We focus on several intertemporal tradeoffs between mining groundwater and importing surface water. Common-property groundwater mining distorts the demand for imported surface water. Reclamation subsidies, in turn, distort both groundwater mining and the decision of when to construct a water-import project. Similarly, the absence of a water market affects groundwater mining and project timing by decreasing the opportunity cost of imported water. Instead of a piecemeal analysis of individual policies, we examine the effects

[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.

[2] 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, p. 326).

of various combinations of laws and policies.

To conduct the analysis, we develop a dynamic model of natural resource depletion with an exhaustible resource (groundwater) and a renewable backstop resource (imported surface water).[3] The model applies basic results on exhaustible resource depletion with a backstop resource (Hotelling 1931; Nordhaus 1973). Two features of the backstop extend the standard model: set-up costs and a flow constraint.[4] Surface water can be imported only after incurring the requisite set-up costs on dams, aqueducts, and pumping stations. In addition, the flow of imported water is constrained by interstate law, aqueduct size, or river flow.[5] Other realistic features of the model include aquifer recharge and an increasing cost of groundwater pumping as the aquifer is depleted.

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 to construct the water-import project. The price then continues to rise to a steady-state value. In the steady state, water supply is the sum of imported water, aquifer recharge, and local surface water. Because the backstop is flow constrained, depletion of the exhaustible resource and production from the backstop can occur simultaneously instead of strictly sequentially as occurs in Nordhaus (1973).

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[3]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.

[4]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).

[5]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.

We apply the model to an important case of western water, Arizona water use. Nonrenewable groundwater deposits in central Arizona have supported the expansion of irrigated agriculture and the growth of the Phoenix and Tucson metropolitan areas. The groundwater has been mined at a rate in excess of 2 million acre-feet per year 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.[6] Construction started in 1973 and deliveries to Phoenix began in 1987. A numerical simulation with parameters on Arizona water demand, supply, and hydrology is developed to assess the effects of water laws and policies. These include: federal subsidies of CAP construction and operating costs under the Reclamation program; a legal restriction on interstate water marketing under the Colorado River Compact; common-property depletion of groundwater; and Arizona's 1980 reform of groundwater law, which bans groundwater mining after the year 2025. These are the major laws and policies that influence water use in the West.

Our results shed light on the decision to build CAP, the deadweight loss from market distortions, and the differential benefits from 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.[7] However, Arizona did not bear the full costs of the project because

[6]Relevant to this study, 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).

[7]The University of Arizona agricultural economist William E. Martin made a point of exhorting, "Even at subsidized CAP water prices, farmers will continue to pump groundwater after CAP construction because groundwater is cheaper!" Martin demonstrated this repeatedly, co-authoring five reports on the topic over

of federal 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 returns to groundwater management are relatively small. This highlights 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 much smaller than the loss introduced by the subsidies. Finally, we find that the deadweight loss of a policy package greatly exceeds the sum of the deadweight losses of the individual policies. This demonstrates the need for a comprehensive analysis in an economic environment with many distortions.

The paper continues with a description of the major laws and policies that govern western water allocation and a review of related research. Section 3 develops the theoretical model, while Section 4 describes the simulation model. The empirical results are reported in three 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. Section 7 demonstrates policy analysis when multiple policies are in effect. A final section concludes and identifies other applications of the modeling framework.

almost two decades: Young and Martin (1967); Kelso, Martin, and Mack (1973); Boster and Martin (1977); Ingram, Martin, and Laney (1982); and Bush and Martin (1986). These reports used farm-budget studies that computed the value of irrigation water to farmers. In effect, Martin made the qualitative point that CAP was being constructed too early. Martin's analysis of the agricultural sector addressed one component of the Arizona water problem, while the present study is a comprehensive dynamic study of the topic. Martin made an unpopular point on his home turf: Arizona politicians (and the dean of the College of Agriculture at the University of Arizona) despised Martin's application of simple economic logic (Reisner 1986, p. 309).

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 an institutional framework for the subsequent analysis of policy-induced inefficiencies in water use. Section 2 describes this structure for the West in general and Arizona in particular.

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 dams and related irrigation works. Impressive statistics were recorded: construction of 355 storage reservoirs, 255 diversion dams, and 18,000 miles of water-transport facilities.[8] Reclamation policy is one of subsidy: to require that local beneficiaries only partially repay on federal financing of a project's construction costs. Economists have a long history of questioning the subsidy policy on efficiency grounds. Most recently, Wahl (1989) estimated that, for the overall Reclamation program, the capital subsidy rate was 51 percent in 1926, increasing to 82 percent in 1975.

The CAP is a massive Reclamation project. It transports water through three aqueducts, running 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 ($5.06 billion) and operating costs ($219.38/acre-foot) are subsidized at rates of 52 percent and 61 percent (*see* Appendix 1). With construction expenditures, the Reclamation subsidies come in the form of various cost subsidies to the agricultural sector (U.S. Department of the Interior 1998). With operating costs, the

[8] Historians aptly refer to the Reclamation program with evocative phrases, such as Reisner's *cadillac desert* and Worster's *rivers of empire.*

federal government sells the electricity required to pump CAP water at a low, administered price rather than a market price.[9]

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 was then authorized in 1968, and construction 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 political 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 the Groundwater Management Act of 1980. CAP deliveries finally began in 1987.

2.2 Surface Water Law and the Colorado River Compact

The prior appropriation doctrine is the primary legal mechanism allocating surface water in the 17 western states (Sax, Abrams, and Thompson 1991). A key characteristic of the doctrine is chronological seniority: a water right established earlier in time is completely satisfied before a right established later. Although the doctrine provides a means to establish tenure certainty in the water right, Burness and Quirk (1979) find that the doctrine distorts decisions on water diversion capacity and allocates water inefficiently. They proceed to show that a water market could correct these inefficiencies (Burness and Quirk 1980). In many western states, however, legal and regulatory restrictions impede or prohibit water exchanges. Markets are now being deregulated in several western states in response to the

[9]Throughout the Colorado River basin, the Reclamation program uses hydroelectricity to subsidize water supply. In the U.S. Senate, Senator Paul Douglas (the economist of Cobb-Douglas fame) strenuously opposed Reclamation's Colorado River Storage Project because of this subsidy (Reisner 1986, p. 147-149).

prospect of sizable gains from trade.

The Colorado River Compact applies prior appropriation principles to interstate water allocation (Burness and Quirk 1980). The Compact is the negotiated settlement among the seven states through which the Colorado River flows. It apportions 2.2 million acre-feet of water per year to Arizona. 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.

Although markets are forming within states, interstate water marketing is more contentious. To date, an interstate market has not been allowed to form along the Colorado River.[11] The laws governing interstate allocation of the Colorado 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. Three legal doctrines are applied in the western states: absolute ownership, prior appropriation, and correlative rights (Gardner, Moore, and Walker 1997). The absolute ownership doctrine is most similar to an open-access commons, as ownership of land overlying an aquifer conveys an unlimited right to pump groundwater. The prior appropriation doctrine of groundwater law creates the ability to restrict entry into a groundwater commons. However, a rule-of-capture still delimits the appropriation

[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."

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

water right. The correlative rights doctrine differs from the other doctrines by not defining a strict rule-of-capture. It effectively grants shares in the groundwater stock in proportion to ownership of the overlying land (i.e., stock quotas). The legal form commonly adopted is the prior appropriation doctrine (12 of 17 states).

The final component of the institutional framework concerns reform of Arizona groundwater law. Before 1980, Arizona groundwater was governed by a variant of the absolute ownership doctrine. When considering CAP, federal officials viewed water-import projects as expensive remedies for bad state policy: if the states had developed efficient groundwater law, aquifer deposits 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]

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 withdrawal; a requirement for metering; an administrative agency for enforcement; and an ability to transfer permitted rights (Arizona Department of Water Resources 1984a; Saliba and Bush 1987). Second, the law bans groundwater mining beginning January 1, 2025. This is characterized as groundwater use at the "safe yield" rate, in which withdrawals equal recharge (Arizona Department of Water Resources 1984a, p. 35).

[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).

3 The Theoretical Model

Analysis of the tradeoff between groundwater extraction and surface water importation requires a framework which models both the economic behavior of agents and the hydrological responses to these actions. In this model, the economic problem is the familiar maximization of discounted net benefits when agents choose the amount of groundwater to pump and the time to construct the water-import project. In addition to the exhaustible groundwater, surface water can be obtained from local sources and water-import projects. However, substantial construction costs must usually be incurred before surface water can be imported, and the flow of imported water is often constrained by river flow, international treaties, or interstate compacts. Our model extends the basic model of resource depletion by modeling surface water importation as a flow-constrained renewable backstop with a set-up cost.[13]

Let $Q(t)$ be the quantity of water consumed[14] in period t, and $U_t(Q)$ be the gross surplus from water in time t where $U_t' > 0$ and $U_t'' < 0$. The model assumes that the infrastructure for utilizing local surface water is already in place, and that local water L can be utilized at cost $c_L L$. Imported water, I, can only be used after a water project is undertaken and a set-up cost, F, is incurred.[15] Once the set-up cost is incurred, water is imported at cost $c_I I$. Before the set-up cost is incurred, the water has market value $v_m I$, where $v_m \geq 0$.[16]

[13]Although we apply the model to water resources, the techniques are generally applicable to any exhaustible resource with a backstop substitute requiring capacity installation.

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

[15]Assumptions here include: imported surface water is subject to an exogenous flow constraint, water is always imported at capacity, and the size of the project is fixed. See Holland (1999) for a discussion of water importation below capacity and of endogenous project size.

[16]The market value of the water, v_m, is the opportunity cost of allocating water to the import project. In this study, v_m represents the gain from selling the water to other users. However, it could also represent the environmental benefit of leaving more water in the river. Since the marginal environmental benefit of

The groundwater is replenished by precipitation and streamflow at a rate R, and by percolation from the water consumed at a rate $\alpha < 1$.[17] Thus, total recharge to the aquifer is $R + \alpha Q(t)$. If the groundwater recharge plus surface water is insufficient to fill demand at the marginal pumping cost, groundwater is "mined." Let $q(t)$ be the quantity of groundwater pumped in period t. Hence, the amount of overdraft mined from the aquifer in period t is $q(t) - R - \alpha Q(t)$.[18] Let the stock variable $S(t) \equiv \int_0^t q(\tau) - R - \alpha Q(\tau) d\tau$ be the cumulative overdraft from the 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.

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

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

leaving some water in the river is almost certainly high, our results understate the costs of the water-import project.

[17] The recharge rate, 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.

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 $t > T$.[19] 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 the 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,[20] steady-state consumption is given implicitly by $Q^{ss} = L + I + R + \alpha Q^{ss}$.

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 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

[19] For ease of exposition, the time subscript is dropped from the utility function in subsequent expressions.

[20] If the water project costs more to build than the surplus which it generates, then it is not efficient to build the water project. Furthermore, if the marginal 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.

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,

$H^- + rF = H^+$, is

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

This equation is derived by augmenting 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

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

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

This equation has an economic interpretation since each side contains the gross benefit from consumption and percolation less pumping and scarcity costs. Thus, 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.[21] 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.[22] 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 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

[21] 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.

[22] 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.

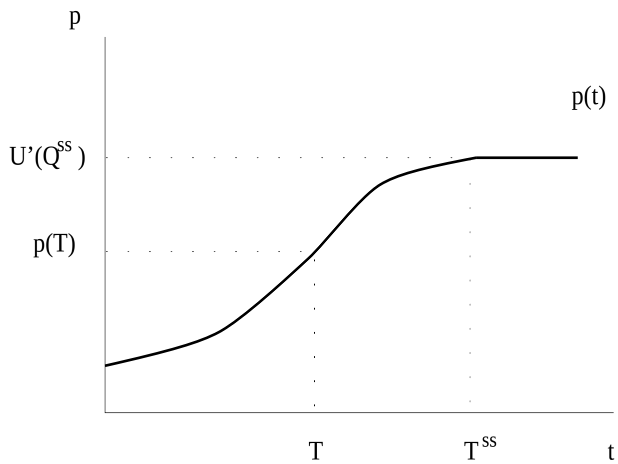

Figure 1: Continuous price path. The water-import project is built when the price reaches the trigger price $p(T) = c_I + v_m + \frac{rF}{I} - \alpha\lambda(T)$.

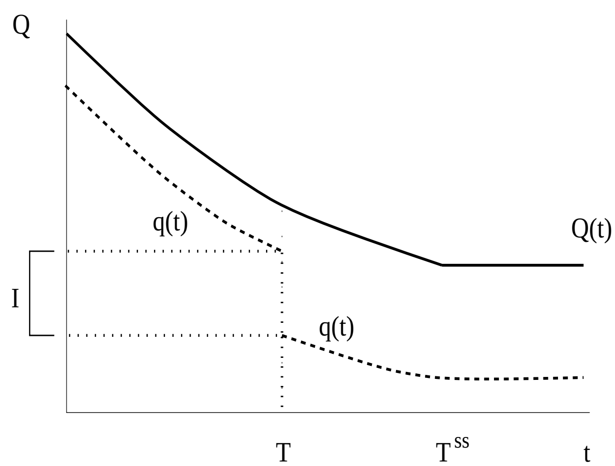

Figure 2: Consumption and extraction paths for a stationary demand curve. Note that the groundwater pumping path, $q(t)$, is discontinuous at T.

imports occur simultaneously in order to smooth consumption.

The efficient time to construct the water-import project can be 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.[23]

The efficient construction timing and trigger price are illustrated in Figure 3.[24] 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

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

= Area(A+B+C+E+F+G)+Area(B+C+D)-Area(B+C+D+E+F+G)

= Area(A+B+C)

[23]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.

[24]For clarity, this illustration ignores local surface water, L.

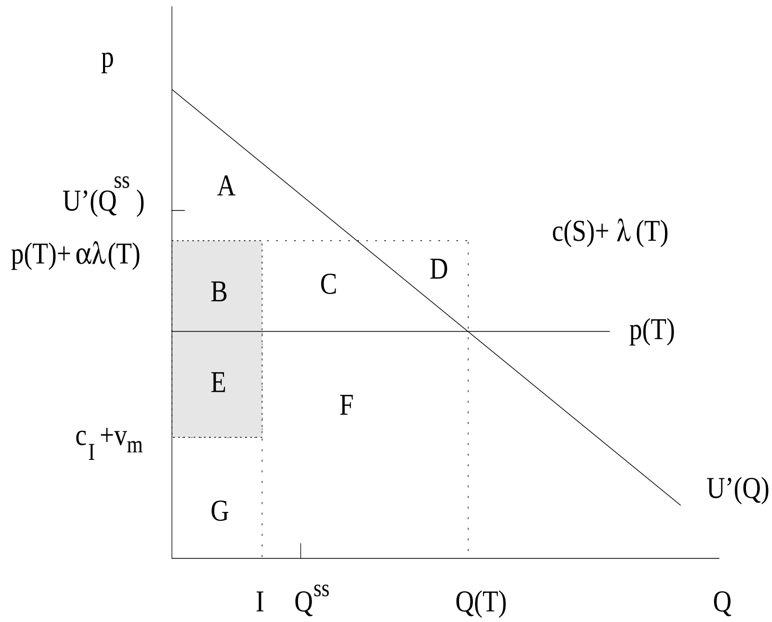

Figure 3: Marginal benefit curve and price when the water-import project is efficiently constructed. The shaded area is the interest payment on the set-up cost rF. Note that at T, the average cost plus the interest payment on the set-up cost exceeds the trigger price $p(T)$ by the percolation benefit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

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. If property rights are properly assigned to price-taking agents, competitive markets would allocate the water efficiently. Section 2 describes three main problems associated with water allocation by markets: project subsidization, prohibition of water marketing, and common-pool extraction of groundwater. To estimate the deadweight loss from various policies, the model above is easily adapted to analyze the effects of these distortions on the dynamic water use decisions of agents.

The analysis looks at 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.[25] This effect can be seen by the change in the trigger price in equation (8) when the costs are subsidized. If the operating costs c_I are subsidized, the price at which the project is built is lower, and hence the project will be built too early. Similarly, if the set-up cost F is subsidized, equation (8) shows that the project will be built too early since the interest payment on the set-up cost $\frac{rF}{I}$ is decreased.

The ban on interstate water marketing is analyzed by noting that if the water cannot be sold, its market value is zero. Since this lowers the opportunity cost of importing water, the effects 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.[26] With this myopic behavior, extractors pump groundwater until the marginal benefit equals the average pumping cost, 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.

[25]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.

[26]An alternative approach would be to solve the common-pool extraction game for a finite number of pumpers. However, Brooks *et al.* (forthcoming) 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.

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.

4 A Simulation Model of Arizona Water Use

The empirical application analyzes the policies affecting water use in Arizona and construction of the CAP. The analysis uses the model developed in Section 3 to estimate the deadweight losses from federal subsidization of CAP and imperfect property rights to groundwater and CAP water. To estimate these losses, the model is parameterized and welfare is computed under various policy scenarios.

4.1 The Simulation Model

Several modifications of the model are required to apply it to Arizona groundwater mining and CAP timing. Since the solution to the model involves solving several differential (integral) equations, a numerical approximation to the model is used. This approximation requires a discrete time version of the model. As suggested in Section 3.1, the most important features in the model solution are the price path $p(t)$ and the efficient time to construct the project, T. If the construction date is fixed, then the price path can 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 which yields the highest welfare is selected as the optimal construction time and optimal extraction path. This is called the efficient baseline.

Welfare effects of the policy scenarios are estimated using a similar approach. To estimate the deadweight loss from the subsidies, the simulation model is applied to find the optimal construction time given subsidized costs. The deadweight loss is then the difference between the baseline welfare and the welfare under the subsidy policy. 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 baseline. 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 underlying the parameters. Table 2 contains the particular parameter values. Appendix 1 describes the data procedures in more detail.

In the model, welfare is measured by summing the stream of discounted consumer and producer surpluses from water use. 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 in 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 applies the simulation model to assess the social value of CAP, the value of CAP to Arizona, and the value of an alternate 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.[27] It shows that the qualitative results reported here are valid for a wide variety of parameters. However, the numerical results are sensitive to the choice of the discount rate, as would be expected.

5.1 The Value of CAP

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 relationship holds for the CAP parameters, construction of the project is efficient. Efficient construction timing builds the project in 2058 (T=108) and generates welfare of $61.090 billion (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. Thus,

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

CAP's incremental value equals \$0.069 billion.[28] Two factors explain this small value.[29] First, CAP is a relatively expensive water supply at over \$5 billion in construction costs and almost \$220/acre-foot in operating costs.[30] 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 construction and operating costs. Under these conditions, Arizona would have wanted to construct CAP in 1971[31] and would have received a net benefit from consumption and transfers of \$61.306 billion(Table 3).[32] 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.

[28]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.

[29]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.

[30]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.

[31]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.

[32]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.

Finally, consider the actual construction date of 1987. 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. These cases are: *Efficiency* = build CAP in 2058 (T=108); *NoBuild* = constrained not to build CAP; *Subsidy* = Arizona's preferred alternative of building CAP in 1971 (T=21); and *Build=1987* = constrained to the actual CAP date of 1987 (T=37).[33] 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.[34] The groundwater pumping paths follow a saw-tooth pattern purely as an artifact of the 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

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

[34] The efficient price grows over time, from $p(0)$=\$99.90 to $p(T)$=\$348.25 to $p(T^{ss})$=\$537.92. Note that as in equation 3, the growth rate of the efficient price is less than the interest rate.

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 the 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 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.[35] 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.[36]

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

The primary political motivation for the construction of CAP was to alleviate groundwater mining. Policy makers knew, however, that CAP alone would not eliminate mining. 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, p. 710). When

[35] 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.

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

Arizona wavered on this provision, Interior Secretary Andrus was dispatched to enforce the law.[37] 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 and a ban on groundwater mining.

6.1 Well-defined Groundwater Property Rights

The 1980 law transforms groundwater rights from common property to reasonably well-defined, transferable rights. The political exchange of CAP subsidies for groundwater reform compares two possible outcomes: (1) building CAP in 1987 with groundwater rights defined under the new law, versus (2) building CAP without subsidy but with groundwater rights defined as common property.[38] In the first outcome, the deadweight loss is \$1.323 billion as computed in the previous section. In the second outcome, groundwater is pumped myopically, overdraft is greater, and the steady-state pumping height is higher: 1611 feet instead of the efficient height of 1538 feet.[39] Given myopic pumping, Arizona's optimal construction timing for CAP would be 2041 and the deadweight loss would be \$0.988 billion (1.6% of

[37]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."

[38]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."

[39]As discussed in Section 3, the steady-state pumping height is higher since myopic pumpers do not consider the effect of current pumping on the steady-state pumping cost.

welfare).[40] Figure 7 shows the groundwater pumping height paths for the two outcomes, *Build=1987* versus *ComProp* in the figure. Myopic pumping in the common property case results in significantly greater pumping height relative to the actual outcome. Based on the relative deadweight losses, we conclude that the political exchange was poor economic policy: the water-project subsidies introduced a larger inefficiency than was removed by the property-rights reform.[41]

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 result in a deadweight loss of \$2.096 billion (the *ComPrp87* pumping height path in Figure 7). 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.[42] From this perspective, the federal government avoided the worst 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

[40]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.

[41]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.

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

pumpers were allowed to pump freely (either with well-defined or common-property rights) (Figure 7). 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 when evaluated with the CAP date set at 1987 and well-defined groundwater rights.

Note that groundwater pumping prior to 2025 increases in response to the ban.[43] 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 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 relative to optimal depletion given the 1987 construction date: too little groundwater pumping after the ban and too much pumping before the ban.

Two factors—the 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 the largest of any single policy or law, e.g., it is greater than the deadweight loss of common-property pumping, $2.096 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 would be distributed? It is unclear. Given these factors, economic pressure to remove or delay the ban should increase steadily as 2025 approaches. Nonetheless, if the

[43] Lee (1978) shows that a price ceiling on a nonrenewable resource increases the depletion rate, relative to efficient depletion, during the phase before the ceiling is binding. Although the government imposes a time constraint in our case, rather than a price constraint, a similar result arises: before the ban on groundwater mining takes effect, groundwater extraction increases relative to the case without the ban.

ban is viewed as credible and is ultimately enforced, it would be a major adverse consequence of the political exchange linking project construction and groundwater reform.

7 Analysis of Multiple Policies

This section conducts an *ex ante* policy analysis of CAP construction. Prior to the construction of a water project, policy-makers make decisions based on the policy environment. As with many Reclamation projects, the policy environment surrounding CAP included many distortions: subsidies, poorly-defined property rights, and bans on groundwater mining and interstate water marketing. In this section, we analyze the relative effects of the individual distortions by altering the policy environment to assess each distortion in isolation. These individual effects are then compared to the actual policy environment.

7.1 Deviations from Efficiency: The Effects of Single Distortions

To analyze the effects of single distortions, we introduce each distortion by itself into the policy environment and then compute the optimal construction timing associated with the distorted setting. We first analyze the price signals relevant to CAP. Federal subsidies of CAP's construction and operating costs motivate policy makers to construct CAP earlier than would be efficient. The inefficient timing implies that the water price and groundwater pumping paths are also distorted. With only the construction cost subsidy, Arizona policy-makers would have constructed CAP in 2031 with a deadweight loss of $0.061 billion(Table 4). With just the operating cost subsidy, policy-makers would have constructed CAP in 2008 with a deadweight loss of $0.378 billion. It is not surprising that the latter has a larger deadweight loss, since the operating cost subsidy makes an annual transfer of

\$0.156 billion versus a single transfer of \$2.615 billion from the construction cost subsidy.

We next analyze the effect of the ban on interstate water marketing. Since Arizona cannot sell the water, the opportunity cost of the river water is zero, i.e., $v_m = 0$. This reduced opportunity cost provides an incentive for Arizona policy-makers to construct CAP too early. Under this scenario, CAP would have been constructed in 2040 with a deadweight loss of \$0.022 billion. This is a relatively minor distortion.

As discussed above, common-pool property rights in groundwater also affect the extraction of groundwater and the construction of CAP. Constructing CAP optimally subject to this myopic pumping implies that CAP would be constructed in 2041 and would yield a deadweight loss of \$0.998 billion. This distortion is costly relative to the individual subsidy policies.

The final distortion which we analyze individually is the ban on groundwater mining. The ban greatly decreases the shadow value of the groundwater, which implies that more groundwater should be pumped earlier and CAP should be constructed later. With just this distortion, CAP should be constructed just as the ban takes effect in 2025 and the deadweight loss would be \$1.005 billion. This is the costliest of all the single distortions since much valuable groundwater is never extracted.

7.2 The Value of Incremental Reform: The Effects of Multiple Distortions

We find that, in terms of deadweight loss, the total effect of the status-quo policy package greatly exceeds the sum of the effects of the individual policies. This is because CAP was constructed in a policy environment of multiple subsidies. As noted in section 5, policy-makers facing subsidized construction and operating costs and a ban on interstate water marketing would have constructed CAP in 1971 at a deadweight loss of \$3.016 billion. However, adding the losses from each of these three policies yields a much smaller loss (\$461 million) than the loss from the combined policies. Intuitively, adding a single distortion near the optimum creates a relatively small change in welfare, while each of the successive distortions add incrementally larger changes. This emphasizes the importance of analyzing multiple policies concurrently in an environment with many distortions.

While adding a single distortion into an efficient allocation has only a small effect, removing a single distortion from an inefficient allocation has a much larger effect. This answers the thought experiment: what is the value of *ex ante* incremental reform? The largest single effect occurs when removing the operating cost subsidy to CAP. Removing this subsidy alone would delay CAP construction by 44 years and yield an incremental benefit of \$2.784 billion. Removing each of the other distortions also yields a relatively large benefit (Table 5). Thus, an additional inefficiency in a distorted environment has a much larger welfare loss than the same distortion introduced into an efficient allocation. Note, however, that once the costs are sunk and the project is constructed, no benefit accrues to the removal of subsidies because the subsidies only affect the construction timing of the project.

8 Conclusion

In *Cadillac Desert*, Reisner's central thesis is that water project development in the American West was extravagant and wasteful. 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 cost and flow constraint. Applying the model to the construction of the Central Arizona Project, we find support for Reisner's central thesis. 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. This provides powerful support for Reisner's central thesis: building CAP in 1987 was worse than never building CAP at all.

As with all Reclamation projects, Arizona's perspective on CAP involves 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 dramatically 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 economic policy in the Arizona case. We find that the returns to groundwater management are not large in the absence of other market distortions, i.e., common-pool extraction yields a deadweight loss of $0.988 billion. Because CAP subsidies create a greater inefficiency, trading CAP subsidies for groundwater reform results 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.[44] A better recommendation, arguably, is that water-import projects simply should not be subsidized.[45]

While the analysis focuses on water-resource development in the western United States, the methodology has application in other regions and time frames. Water consumption in China and India, for example, is projected to increase by over 50 percent between 1995 and 2020 (Rosegrant, Ringler, and Gerpacio 1997). Major regions of those countries are currently mining nonrenewable groundwater reserves. 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).[46] Global warming, consequently, could trigger a second prolonged period of water-resource development in the 21st century.

[44]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).

[45]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.

[46]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. 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 actual and projected 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, one of the major urban areas served by the CAP. Tucson's estimated price elasticity of demand equals -0.624 (Agthe, et al. 1986); its water price equals \$689.31/acre-foot (Agthe and Billings 1981); and its water quantity equals 206,000 acre-feet (Arizona Department of Water Resources, Tucson Active Management Area 1984). Second, Tucson's demand equation is adjusted based on the ratio of total population in the three counties to population in Tucson. The choke price remains constant, while the quantity intercept shifts equi-proportionately to the population ratio. 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 similarly adjusted based on actual or projected population levels in the three-county 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. We assume that the region's population stabilizes in 2025. Population data are from Arizona Department of Water Resources, Phoenix Active Management Area (1984, 1991); Arizona Department of Water Resources, Pinal Active Management Area (1985); Arizona Department of Water Resources, 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 using groundwater 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; total agricultural water use in 1980 of 3,876,000 acre-feet (Arizona Department of Water Resources, Phoenix Active Management Area 1984; Arizona Department of Water Resources, Pinal Active Management Area 1985; Arizona Department of Water Resources, Tucson Active Management Area 1984); and the mean price (groundwater pumping cost) of $75.74/acre-foot. The mean price reflects an adjustment from 1984 to 1980 aquifer conditions. The resulting 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 constant over time.

(2) Central Arizona Project.

Annual CAP delivery. CAP transports Colorado River water from Arizona's western border to south-central region. 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, p. 60). A sensitivity analysis is completed using an annual delivery of 1,144,100 acre-feet. The latter number is used in simulations of interstate markets for Colorado River water (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 by the Central Arizona Water Conservation District (the legal entity created to manage repayment to the federal government). The repayment incorporates costs allocated to irrigation water supply and M&I water supply (U.S. Department of the Interior 1998, p. 87). Computations of subsidized set-up costs also include the effects of 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 from a retail market price for electricity in the western United States of 41.7 mills/kilowatt-hour (Congressional Budget Office 1997, p. 42) and the observed quantity of electricity used to transport CAP deliveries (U.S. Department of the Interior 1998, p. 68-73). 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, p. 73). Third, it includes projected operating costs of transporting water from the CAP aqueduct to retail water consumers. This equals $36.22/acre-foot (Bush and Martin 1986, p. 67-71).

We also conduct a sensitivity analysis on the electricity cost of pumping CAP water. Using a higher price for electricity in the lower Colorado River basin (Booker and Young's (1994) estimate of 58.1 mills/kilowatt-hour), 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. Both adjustments involve charges levied on CAP customers by the Central Arizona Water Conservation District (Central Arizona Project 1999). The district's electricity charge equals \$28.37/acre-foot. It would include the low, administered price for electricity that the federal government charges for pumping and conveyance of CAP water. The district's charges for operating costs other than electricity equal \$33.87/acre-foot, which is lower than the CAP operating costs reported by the Bureau of Reclamation.

Opportunity cost of CAP water. Two levels of opportunity cost for CAP water are applied at different points in the analysis: zero and \$36.89/acre-foot. One mechanism to create an efficient opportunity cost is through an interstate water market. We thus apply the market-clearing price from a simulated Colorado River market, \$36.89/acre-foot (Booker and Young 1994). In contrast, without an interstate water market in the Colorado River basin, Arizona faces no opportunity cost for CAP water.

The Colorado River market price also incorporates a water transport loss factor to convert the price 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 (Arizona Department of Water Resources, Phoenix Active Management Area 1984, 1991; Arizona Department of Water Resources, Pinal Active Management Area 1985; Arizona Department of Water Resources, 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.

Based on information in the central Arizona planning documents, the area overlying the aquifer in the three counties of central Arizona equals 5,529,139 acres. The specific yield of the underground reservoir is 0.055 feet of water per vertical foot of the aquifer. This number is obtained using estimates of the volume of water in storage to a depth of 1,200 feet prior to any groundwater pumping (U.S. Department of the Interior 1986b). Finally, pumping depth in 1950 is developed using a three-step procedure. One, depth-to-water in 1985 is estimated by taking the mean of readings at 318 U.S. Geological Survey observation wells in the region during that year (U.S. Department of the Interior 1986a). Two, this is converted to depth-to-water in 1950 by running the aquifer model between 1985 and 1950. Estimates of annual groundwater pumping for 1950-84 (U.S. Department of the Interior 1986a), combined with the natural recharge rate and return-flow recharge coefficient, produce an estimate of depth-to-water in 1950. Three, a conversion factor of 98 feet translates depth-to-water into pumping depth. "Pumping depth" is lower than "depth-to-water" because groundwater pumping creates a cone of depression at individual wells. The conversion factor of 98 feet is an empirically-observed average for Arizona (U.S. Department of Commerce 1986). These procedures produce the initial condition for the analysis: a pumping depth of 88.0 feet in 1950.

Two other comments pertain to the aquifer model. First, a simplifying assumption with the model is that, as groundwater mining occurs, the water table remains uniform within the aquifer independently of the spatial location of pumping. This is the conventional assumption in previous economic research. Second, hydrological evidence indicates that the aquifer depth, or thickness, exceeds 2,000 feet in many sub-basins within central Arizona (Arizona Department of Water Resources 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 of an aquifer, a share of water applied above ground percolates into the aquifer. Based on information in the central Arizona planning documents, the weighted average return-flow recharge coefficient for the three counties of central Arizona equals 0.257.

Groundwater pumping cost. Groundwater depletion involves drilling wells into aquifer deposits, then pumping groundwater to the land surface. Groundwater depletion costs depend on energy costs for water pumping; maintenance costs; and well construction costs. Based on Bush and Martin (1986, p. 9-10, 18-19), 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 (Arizona Department of Water Resources, Phoenix Active Management Area 1984, 1991; Arizona Department of Water Resources, Pinal Active Management Area 1985; Arizona Department of Water Resources, Tucson Active Management Area 1984, 1996). The rivers in the region include the Salt, Verde, Gila, Agua Fria, and Santa Cruz. This water is supplied at a cost of $36.22/acre-foot, which is the 1980 urban flood irrigation price charged by the Salt River Project in central Arizona (Regli 1985, p. 23).

(5) Interest rate

The analysis applies an interest/discount rate of 3.21%. This rate serves two functions: (1) to produce a present value net benefit from intertemporal water use in the dynamic model and (2) for compounding and discounting of annual CAP construction expenditures between 1972 and 2002 to obtain a 1987 present value for CAP set-up costs. The rate of 3.21% is the average real interest rate for 1972-1997. As a basis for finding the average, annual rates are computed as the difference between the 30-year Treasury bond rate and inflation rate (Executive Office of the President, Council of Economic Advisors 1999). Sensitivity analysis is conducted with the interest/discount rate.

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.[47]

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. 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

[47]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 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: Pertinent Public Policies and Legal Doctrines**

General Category	**Specific Case**	**Major Policy 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	No	108	\$61.090 bill	—	\$61.090 bill
NoBuild	No	n.a.	\$61.021 bill	\$0.069 bill	\$61.021 bill
Subsidy	Yes	21	\$58.074 bill	\$3.016 bill	\$61.306 bill
Build=87	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 costs. The *Build=87* case constrains the planner to construct CAP in 1987.

Table 4: **Deviations from Efficiency**

Policy Distortion	T	Welfare	DWL
None	108	\$61.090 bill	–
F subsidy	81	\$61.029 bill	\$0.061 bill
c_I subsidy	58	\$60.712 bill	\$0.378 bill
$v_m = 0$	90	\$61.068 bill	\$0.022 bill
Myopic pumping	91	\$60.102 bill	\$0.988 bill
Ban=2025	75	\$60.085 bill	\$1.005 bill

Table 5: **The Value of Incremental Reform**

Policy Distortions	Incremental Reform	T	DWL	Benefit of Reform
F & c_I subsidy $v_m = 0$	*None*	21	\$3.016 bill	–
c_I subsidy $v_m = 0$	F subsidy removed	44	\$0.897 bill	\$2.118 bill
F subsidy $v_m = 0$	c_I subsidy removed	65	\$0.232 bill	\$2.784 bill
F & c_I subsidy	$v_m > 0$	35	\$1.475 bill	\$1.541 bill

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.