Cadillac Desert revisited: property rights, public policy, and water-resource depletion

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Abstract:

To alleviate Arizona's dependence on groundwater, the federal government subsidized construction of the Central Arizona Project (CAP) to import water from the Colorado River. In exchange for the subsidy, Arizona reformed its groundwater law to eliminate common-property pumping and to ban groundwater mining after the year 2025. We build a model of water resource development in which imported water is a capacity constrained backstop. The model is applied to quantify the welfare effects of alternative CAP construction dates and Arizona groundwater laws. We reach two general conclusions. First, CAP was completed 86 years too early, in 1987, at a deadweight loss of \$2.612 billion. Ironically, construction in 1987 yielded lower surplus than never constructing CAP. Second, the political exchange of reform for subsidy introduced a greater loss (\$2.612 billion) than it corrected (\$0.810 billion). The exchange was worse than doing nothing at all.

Keywords: Exhaustible resource; Setup costs; Backstop; Natural resource development; Water; Central Arizona Project

Article:

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 1249 ft**,** 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 [42].

1. Introduction

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

Water use in the West frequently involves the intertemporal tradeoff between mining local groundwater and building a project to import water from a distant source. [2] The problem is made complex in that the major laws and policies—common-property groundwater pumping, nontransferable water rights, groundwater mining bans, and Reclamation subsidies—interact to distort demand and supply across water sources. For example, common-property groundwater mining increases demand for imported water since the aquifer is depleted too rapidly. Reclamation subsidies, in turn, distort both groundwater mining and the timing decision on water-project construction. To analyze these distortions, we develop a model of natural resource depletion with a nonrenewable resource (groundwater) and a renewable backstop (imported surface water).[3] The model extends basic results on nonrenewable resource depletion with a backstop [30,38] to analyze two additional features of the backstop: setup costs and a flow constraint. [4] Setup costs for constructing dams, aqueducts, and pumping stations must be incurred before any water can be imported. In addition, the flow of imported water is constrained by interstate law, aqueduct size, or river flow.

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

In central Arizona, nonrenewable groundwater reserves supported the expansion of irrigated agriculture and the growth of the Phoenix and Tucson metropolitan areas. Groundwater mining in excess of 2 million acre ft per year has occurred since the 1950s. To augment dwindling groundwater reserves and to establish clear title to water from the Colorado River, Arizonans proposed the CAP to transport over 1 million acre ft of water per year from the western border of the state to central Arizona.[5] Construction started in 1973 and deliveries began in 1987. Although CAP imports substantial quantities of water to central Arizona, increased demand and exhaustion of groundwater reserves imply that current water consumption levels are not sustainable.

A numerical simulation of the model with parameters on Arizona water demand, supply, and hydrology is developed to assess several policies. These include: federal subsidies of CAP construction and operating costs; a restriction on interstate water marketing under the Colorado River Compact; common-property depletion of Arizona groundwater; and Arizona's 1980 reform of groundwater law, which bans groundwater mining after 2025.

Our results shed light on various policy choices. First, we estimate that CAP was built 86 years too early. Due to the relative abundance of groundwater and the high costs of the project, welfare would have increased by delaying the project and using the available groundwater. [6] However, Arizona did not bear the full costs of the project because of federal subsidies. Consequently, the project was actually built quite close to Arizona's preferred time. 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 relatively small returns to groundwater management highlight another poor policy choice. The federal government agreed to subsidize CAP only if Arizona reformed its groundwater law. The benefit from removing the common-pool distortion, however, was smaller than the loss introduced by the subsidies. Finally, the deadweight loss from the ban on groundwater mining in 2025 raises doubt about the ban's credibility. As suggested by theory [37], groundwater pumping prior to 2025 increases in response to the ban. This explains a portion of the deadweight loss, while unused groundwater explains the rest.

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

2. Western water law and policy

A governance structure of Reclamation policy, state water laws, and interstate law on shared river systems guides water allocation in the West. Previous research on these topics analyzes the isolated effects of individual policies instead of their interrelated effects.

2. 1. Federal reclamation policy and the CAP

Beginning with the Reclamation Act of 1902, the Bureau of Reclamation pursued its mission of western settlement through an ambitious program to construct and subsidize dams and related irrigation works. [7] Reclamation's subsidies require local beneficiaries to repay only a portion of federal financing of a project's construction costs. Economists have long questioned the subsidies on efficiency grounds (e.g., [7,18,27]). In particular, Freeman [22] finds that costs outweighed benefits for many Reclamation projects, especially those constructed after 1950. Most recently, Wahl [56] estimated that, for the overall Reclamation program, the capital subsidy rate was 82 percent in 1975.[8]

The CAP is a massive Reclamation project, transporting water over 300 miles from the Colorado River on the western border of Arizona to south-central Arizona. Along the route, a series of pumping plants lift water over 2000 ft in elevation. CAP's construction costs (approximately $5 billion) and operating costs (approximately $275/acre ft) are subsidized at rates of 52 and 61 percent (see Appendix A). With construction costs, Reclamation policy creates various subsidies to the agricultural sector. With operating costs, the federal government sells the electricity required to pump CAP water at a low, administered price rather than a market price.

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

2.2. Surface water law and the Colorado River

Two interstate compacts, a federal law, and a US Supreme Court decision combine to define the states' entitlements to Colorado River water [45]. Arizona's entitlement is 2.2 million acre ft per year. The entitlement, however, does not create clear title for Arizona; as a tenet of water law, the beneficial use provision stipulates that agents establish tenure certainty in the right only through physical diversion.[9] Thus, Arizona's valid title to its endowment remained uncertain until CAP began delivering water.

Burness and Quirk [13] find that western water law promotes inefficient river development and water use. They proceed to show that a water market could correct these inefficiencies [14]. Many studies estimate the gains from trade that could occur with voluntary transfer of water rights (e.g., [9,21,55,8]). Although markets are being deregulated within several states, an interstate market has not formed along the Colorado River.[10] The laws governing the river's allocation do not explicitly authorize interstate marketing, and some provisions implicitly prohibit marketing [39]. Consequently, Sections 3 and 4 study policies in which Arizona is prohibited from interstate water marketing.

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 [23]. Theory predicts that agents undertake an inefficiently rapid pace of mining when a rule-of-capture determines groundwater rights [1 1]. Several studies estimate the benefit of groundwater management using simulations of common-property depletion (e.g., [20,24,35]).

Arizona law prior to 1980 defined groundwater as a commons; ownership of land overlying an aquifer conveyed an unlimited right to pump water. When considering CAP, federal officials viewed water-import projects as expensive remedies for bad state policy: if the states had developed efficient law, aquifers would not be exhausted so rapidly. For the carrot of the CAP, the Carter Administration wielded a stick: Arizona must reform its groundwater law or Reclamation would not construct CAP [42]. Passage of the Arizona Groundwater Management Act of 1980 assured continued federal subsidy of CAP.[11]

Arizona's 1980 groundwater law has two salient features. First, it created reasonably well-defined, transferable property rights in groundwater [6,43]. Second, the law bans groundwater mining beginning 1 January 2025 by restricting groundwater use to the "safe yield" rate, in which net depletion equals recharge [6]. The cost of a ban on groundwater mining has not been studied empirically. In related theory, however, Long [37] shows that nationalization of a nonrenewable resource increases extraction in advance of the date of nationalization.

3. The theoretical model

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

Let $Q(t)$ be the quantity of water used[12] at time t, and $U_t(Q(t))$ be the gross surplus from water at time t where $U_t' > 0$ and $U_t'' < 0$.[13] Water supply comes from three sources: local surface water, imported water, and groundwater. The quantity of local surface water available is L and can be utilized at cost $c_L L$. Let I be the quantity of water available to import from a distant river.[14] If the water is not imported, it has a value of $v_m \geq 0$ per unit.[15] Water can be imported only after construction of a project. Let F be the setup costs of construction and $c_I I$ be the operating costs of importing I units of water after the project is constructed.

The groundwater is replenished by R units of recharge from precipitation and streamflow and by percolation of the water used at a rate $0 \leq \alpha < 1$.[16] Thus, total recharge to the aquifer is $R + \alpha Q(t)$.[17] If groundwater pumping is greater than total recharge, then groundwater is being "mined." Let $q(t)$ be the quantity of groundwater pumped at t. Hence, the amount of overdraft mined from the aquifer is $q(t) — R — \alpha Q(t)$.[18] Let the state variable $S(t) \equiv \int_o^t \{q(\tau) — R — \alpha Q(\tau)\} d\tau$ be the cumulative overdraft from the groundwater stock. Since the pumping cost at time t depends on the height that groundwater must be pumped, the pumping cost is an increasing function of cumulative overdraft. Let $c(S(t)) \bullet q(t)$ 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.[19]

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 gross surplus less costs, where r is the discount rate. The planner's problem is

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

where water usage is $Q(t) = L + q(t)$ for $t < T$ (i.e., before the project is built) and $Q(t) = L + I + q(t)$ for $t > T$. The first integral in the planner's objective is discounted net surplus before the project has been built and before water is imported. Net surplus is the benefit from using and marketing water less the costs of pumping groundwater and supplying local surface water. The second term in the objective is the present value of the setup 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 water usage is given implicitly by $Q^{ss} = L + I + R + \alpha Q^{ss}$.

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

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

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

Since $\lambda(t)$ is the shadow value of an additional unit of groundwater at time t, $\lambda(t)$ is the opportunity (scarcity) cost of pumping an additional unit of groundwater at time t. The term $\alpha\lambda(t)$ is then the marginal percolation benefit of using an additional unit of water at time t. Eq. (2) thus equates the marginal benefits from water usage and percolation with the marginal pumping and scarcity costs.[21] Eq. (3) is the equation of motion of the shadow value. Since the growth rate of the r - $\frac{c'q}{\lambda}$, the Hotelling r-percent rule takes into account the effect of pumping today on all future pumping costs.[22] In the steady state, the current shadow value is constant, i.e., .$\dot{\lambda} = 0$. Eq. (3) implies that the steady-state scarcity cost of water is $\frac{c'q}{r}$, which is the marginal increment to the total pumping cost from pumping an additional unit of groundwater capitalized at rate r. Eq. (2) then implies that cumulative overdraft in the steady state, S^{ss}, is given by

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

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

To compute the efficient time to construct the project, first note that the 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 $Q^{+} \equiv lim_{t\downarrow T}$. Following Hartwick *et al.* [26], the first-order condition for optimal project timing, $H^{-} + rf = H^{+}$, is

$$\begin{aligned} &e^{-rT}[U(Q^{-}) - c(S)q^{-} - c_L L + v_{\mathrm{m}} I - \lambda(T)(q^{-} - R - \alpha Q^{-})] + re^{-rT}F \\ &\quad - \{e^{-rT}[U(Q^{+}) - c(S)q^{+} - c_L L - c_I I - \lambda(T)(q^{+} - R - \alpha Q^{+})]\} = 0. \end{aligned} \tag{5}$$

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

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

Note that the first three terms are the gross benefit from water usage and percolation less pumping and scarcity costs. The right-hand side is also the net benefit, but additionally includes the operating plus opportunity costs of the imported water. Thus, the equation implies that the project should be built when the net benefit from building the project exceeds the net benefit without the project by the interest payment on the setup 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 water usage. If $c_I + v_m + \frac{rf}{I} < U'(Q^{ss})$ (i.e., if the project costs are not too large), Holland [29] shows that $p(t)$ is continuous and defines a competitive equilibrium price path.[23] The price $p(t)$ increases through time until the steady state is reached at time T^{ss} , after which the price is constant at $p(T^{ss}) = U'(Q^{ss})$. Using this price path, the water usage and extraction paths can be found from the marginal valuation curve. Usage and extraction paths for a stationary demand curve are illustrated in Fig. 1. Since the price path is increasing and continuous, the usage path is decreasing and continuous. However, groundwater pumping is discontinuous at T when water importation commences. This discontinuous decrease in groundwater pumping is precisely offset by the discontinuous increase in water importation. Note that between T and T^{ss}, the flow constrained backstop implies that groundwater pumping and water imports occur simultaneously in order to smooth consumption. Groundwater mining ceases at T^{ss}.

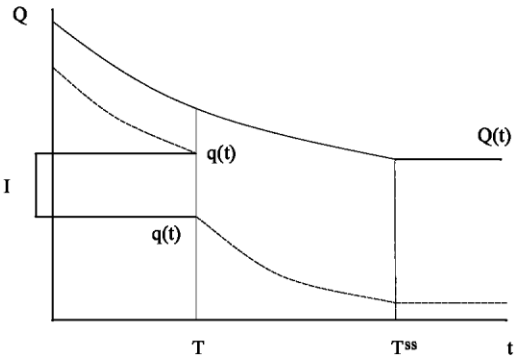


Fig. 1. Water usage and extraction paths for a stationary demand curve. Note that the groundwater pumping path, $q(t)$, is discontinuous at T.

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

$$c(S) + \lambda(T) = c_I + v_{\mathrm{m}} + \frac{rF}{I}. \qquad (7)$$

Eq. (2) then implies

$$p(T) + \alpha\lambda(T) = c_I + v_{\mathrm{m}} + \frac{rF}{I}. \qquad (8)$$

Thus, the efficient time to construct the water-import project is when the marginal benefit of water usage plus recharge exceeds the marginal importation cost by the per unit interest payment on the setup 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.[24]

3.2. Modeling inefficiencies in water use

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

The analysis addresses two project subsidies: a setup (construction) cost subsidy and an operating cost subsidy. These subsidies distort the optimal decisions of a project planner in contrast to the efficient decisions of a social planner. In particular, let F^{AZ} be the subsidized setup cost and c_I^{AZ} be the subsidized operating costs. A project planner facing these subsidized costs would then have an incentive to construct the project at an inefficient time. To see this, consider the trigger price for efficient project construction from Eq. (8). With the subsidized costs, this equation becomes

$$p^{AZ}(T^{AZ}) + \alpha\lambda^{AZ}(T^{AZ}) = c_I^{AZ} + v_{\mathrm{m}} + \frac{rF^{AZ}}{I}.$$

Since the subsidized costs are lower than the true costs, the planner has an incentive to construct the project earlier when the marginal valuation of water is lower.[25] Note that Eq. (7) implies that when the project is built the pumping cost equals the subsidized costs. Since the subsidized costs are less than the true costs, the project is substituting more expensive imported water for the cheaper groundwater.

Similarly, the prohibition on interstate water marketing (as described in Section 2.2) can be analyzed by noting that if the imported water could not be sold, its opportunity cost would be reduced. For example, the imported water I may have zero opportunity cost to the project planner if it cannot be marketed. Let v_m^{AZ} be this reduced opportunity cost. The right-hand side of the trigger price equation now becomes $c_I^{AZ} + v_m^{AZ} + \frac{rfAZ}{I}$. If the project planner faces a reduced opportunity cost for the imported water, the incentive is again to construct the project too early.[26]

To estimate the welfare loss due to common-pool extraction of groundwater, we follow Gordon [25] in assuming rent dissipation in each period.[27] With this myopic behavior, extractors pump groundwater until the marginal benefit equals the average pumping cost, i.e., Eq. (2) implies that $U'(Q) = c(S)$ in each period. Thus, groundwater is pumped too fast in the common-pool equilibrium. Since pumping costs increase with cumulative overdraft, pumping decreases over time and consumption is smoothed to a steady state. Note that steady-state water usage 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 Eq. (4) shows that too much groundwater is mined in the common-pool equilibrium.

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

4. A simulation model of Arizona water use

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

4. 1. Numerical solution of the model

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

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

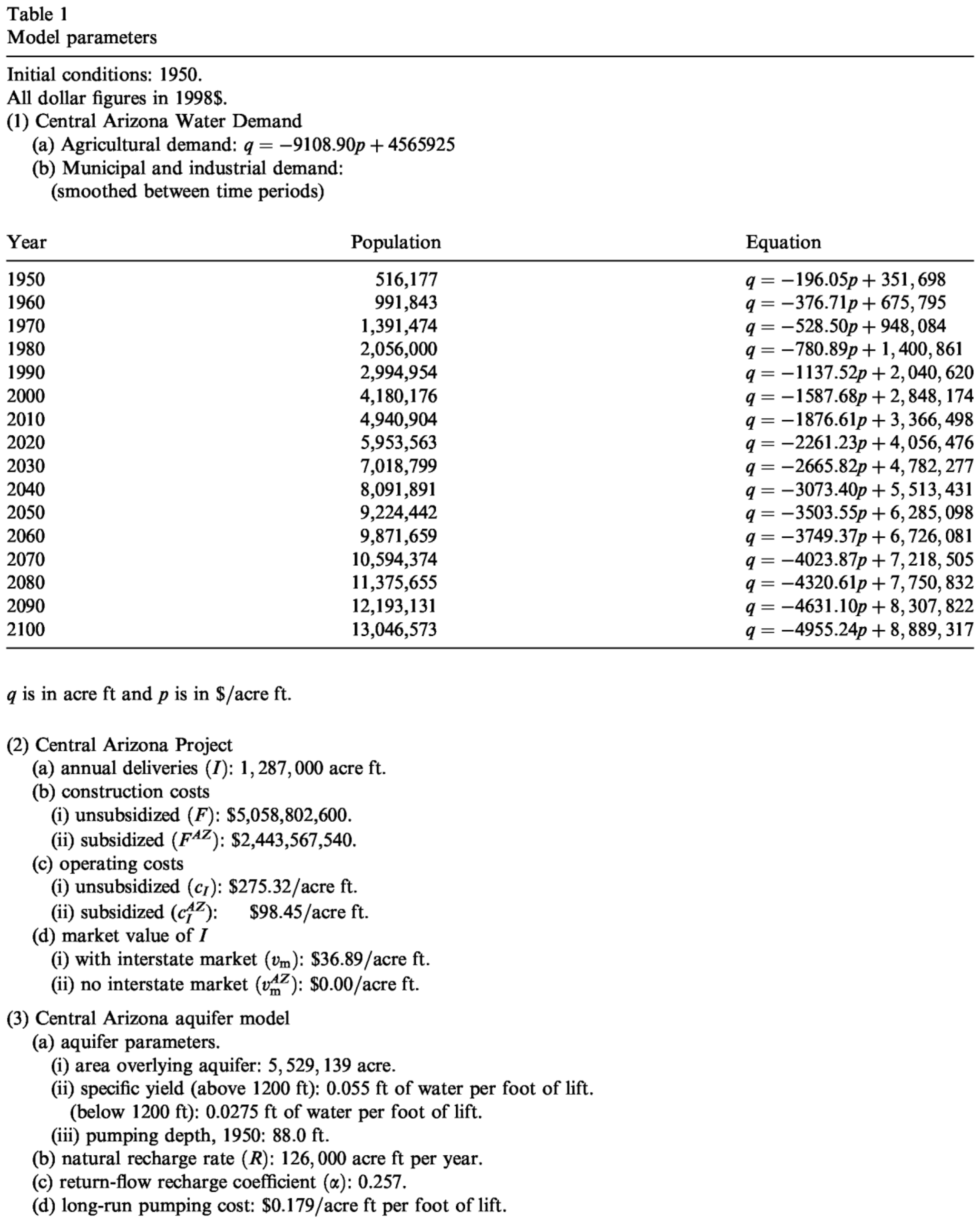


Table 1
Model parameters

Initial conditions: 1950.
All dollar figures in 1998\$.
(1) Central Arizona Water Demand
(a) Agricultural demand: $q = -9108.90p + 4565925$
(b) Municipal and industrial demand:
(smoothed between time periods)

Year	Population	Equation
1950	516,177	$q = -196.05p + 351,698$
1960	991,843	$q = -376.71p + 675,795$
1970	1,391,474	$q = -528.50p + 948,084$
1980	2,056,000	$q = -780.89p + 1,400,861$
1990	2,994,954	$q = -1137.52p + 2,040,620$
2000	4,180,176	$q = -1587.68p + 2,848,174$
2010	4,940,904	$q = -1876.61p + 3,366,498$
2020	5,953,563	$q = -2261.23p + 4,056,476$
2030	7,018,799	$q = -2665.82p + 4,782,277$
2040	8,091,891	$q = -3073.40p + 5,513,431$
2050	9,224,442	$q = -3503.55p + 6,285,098$
2060	9,871,659	$q = -3749.37p + 6,726,081$
2070	10,594,374	$q = -4023.87p + 7,218,505$
2080	11,375,655	$q = -4320.61p + 7,750,832$
2090	12,193,131	$q = -4631.10p + 8,307,822$
2100	13,046,573	$q = -4955.24p + 8,889,317$

q is in acre ft and p is in \$/acre ft.

(2) Central Arizona Project
(a) annual deliveries (I): 1,287,000 acre ft.
(b) construction costs
(i) unsubsidized (F): \$5,058,802,600.
(ii) subsidized (F^{AZ}): \$2,443,567,540.
(c) operating costs
(i) unsubsidized (c_I): \$275.32/acre ft.
(ii) subsidized (c_I^{AZ}): \$98.45/acre ft.
(d) market value of I
(i) with interstate market (v_{m}): \$36.89/acre ft.
(ii) no interstate market (v_{m}^{AZ}): \$0.00/acre ft.

(3) Central Arizona aquifer model
(a) aquifer parameters.
(i) area overlying aquifer: 5,529,139 acre.
(ii) specific yield (above 1200 ft): 0.055 ft of water per foot of lift.
(below 1200 ft): 0.0275 ft of water per foot of lift.
(iii) pumping depth, 1950: 88.0 ft.
(b) natural recharge rate (R): 126,000 acre ft per year.
(c) return-flow recharge coefficient (α): 0.257.
(d) long-run pumping cost: \$0.179/acre ft per foot of lift.

Table 1 (*continued*)

(4) Local surface-water supply
(a) deliveries (L): 984,000 acre ft per year.
(b) cost (c_L): \$36.22/acre ft.

(5) Interest rate (r): 3.21%

4.2. Model parameters

Table 1 reports parameter values for water demand, supply, and aquifer conditions for the three-county region in central Arizona and for the CAP. Here we provide an overview of the model parameters. The appendix describes the development of the parameters in more detail.

Aggregate demand is composed of two linear demand equations: municipal and agricultural. The municipal demand equation shifts intertemporally 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 1).[28]

Parameters for the CAP include annual deliveries I, construction costs, operating costs, and market value of CAP water (Table 1). The CAP parameters are developed primarily from data contained in the Bureau of Reclamation's analysis of repayment obligations of CAP beneficiaries (US Department of the Interior [51]). The unsubsidized setup cost F is the present value in 1987 (at the time CAP service begins) of actual and projected annual CAP construction expenditures between 1972 and 2002. The subsidized setup cost F^{AZ} is the present value in 1987 of projected capital repayments of water users. Unsubsidized operating costs c_I include electricity costs evaluated at a market price and conventional operating and maintenance costs. Subsidized operating costs c_I^{AZ}, in contrast, evaluate electricity costs at an administered price. Finally, the market value of CAP water v_m is the price of water from a simulated interstate market for the Colorado River basin [9]. Arizona perceives this value v_m^{AZ} to equal zero in the absence of a market.

The aquifer for central Arizona is modeled as a single-cell aquifer, cf. [12,24,20]. The model is constructed from data reported in hydrological investigations [52–54] and collected in planning documents for implementation of the Arizona Groundwater Management Act of 1980. Based on Bush and Martin [15], 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.[29]

5. Perspectives on the value of CAP

This section initially applies the simulation model to estimate the social value of CAP and the value of CAP to Arizona. We next study the value of an alternative site for the project. The simulation model uses initial conditions in the year 1950. All welfare levels are reported as a 1950 present value using 1998 dollars.

5. 1. The value of CAP

Four model solutions are considered to shed light on the value of CAP: the efficient solution (labeled the Efficiency case); a solution in which CAP is never constructed (the NoBuild case); Arizona's preferred solution given the distorted costs of imported water (the Subsidy case); and a solution in which CAP is constructed at its actual completion date in 1987 (the Build = 1987 case). The model solves for project timing in the Efficiency and Subsidy cases, but takes project timing as given in the NoBuild and Build = 1987 cases. In addition to measuring economic welfare, we measure "net benefit to Arizona" to reflect Arizona's perspective on CAP construction.

Begin with the efficiency question: Should the CAP be built and, if so, when? If $c_I + v_m + \frac{rf}{I} < U'(Q^{ss})$; the trigger price is less than the steady-state price. Since this inequality holds for the CAP parameters, construction of the project is efficient. Efficient construction timing builds the project in 2073 (T = 123) and generates welfare from efficient water use of $74.172 billion. This is the Efficiency case in Table 2.

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 $74.077 billion in welfare. This is the NoBuild case (Table 2). CAP's incremental value thus equals $0.095 billion.[30] Two factors explain this small value. First, CAP is a relatively expensive water supply at over $5 billion in construction costs and $275/acre ft in operating costs.[31] Second, CAP augments substantial local, renewable water resources exceeding 1.1 million acre ft per year. If CAP were never built, groundwater mining would continue deeper into the aquifer, last longer, and mine an additional 307.3 million acre ft 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? Arizona's perspective reflects the distortions of both Reclamation policy and an insecure property right. Reclamation's subsidy policy creates a clear incentive for early construction of CAP. The insecure property right to Colorado River water creates a second incentive for early construction. Without the CAP, Arizona would gain no value from its entitlement to Colorado River water. The difference between welfare and net benefit to Arizona in the Efficiency and NoBuild cases reflects this second incentive. In each case, Arizona's net benefit is about $1.5 billion lower than welfare because Arizona does not receive the market value of Colorado River water (v_mI) prior to CAP construction. From Arizona's perspective, then, the Subsidy case is the preferred outcome; it generates roughly $1 billion more in net benefit than either Efficiency or NoBuild. The Subsidy case builds the project in 1991 and explains Arizona's push for early construction.[32]

Finally, consider the actual construction date of 1987 (the Build = 1987 case). CAP's actual timing in 1987 is quite similar to Arizona's preferred timing in 1991. However, actual timing is more than eight decades earlier than efficient timing. The deadweight loss from completing CAP in 1987 is $2.612 billion, which far exceeds CAP's incremental value. Ironically, building CAP in 1987 was worse than never building CAP at all.

Table 2
The value of CAP

CAP construction alternative	T	Welfare	Deadweight loss	Subsidy/marketing	Net benefit to Arizona
Efficiency case	123	$74.172 bill	—	No/No	$72.676 bill
NoBuild case	n.a.	$74.077 bill	$0.095 bill	n.a./No	$72.550 bill
Subsidy case	41	$71.991 bill	$2.181 bill	Yes/No	$73.602 bill
Build = 1987 case	37	$71.560 bill	$2.612 bill	Yes/No	$73.594 bill

Notes: "n.a." means "not applicable" because CAP is not constructed in this simulation. The NoBuild case constrains the planner not to construct CAP. The Subsidy case optimizes benefits to Arizona given the subsidized CAP costs and the ban on interstate water marketing. The Build = 1987 case constrains the planner to construct CAP in 1987. The subsidy/marketing column refers to whether Arizona receives federal subsidies for CAP and/or is allowed to market Colorado River water prior to CAP construction.

Figs. 2 and 3 show the groundwater pumping and water price paths through 150 years for these four cases of CAP timing (Efficiency, NoBuild, Subsidy, and Build = 1987).[33] The groundwater pumping paths shift down by approximately 1.3 million acre ft (CAP capacity) when CAP is constructed at the various times in the different cases. This is the pattern depicted in Fig. 1 for the theoretical model. In contrast, the price paths are continuous, as would be expected.[34]

Population growth explains the intertemporal increase in groundwater mining through $t = 100$ in the four cases (Fig. 2). Although groundwater pumping cost increases with cumulative overdraft, the population-induced growth in water demand exerts a larger effect than cost. This explains the anomaly of both groundwater quantity and water price increasing for a period of time. After population stabilizes in $t = 150$, groundwater pumping decreases until reaching a steady state. The ultimate decline in pumping follows from the standard Hotelling result and the increase in pumping cost with cumulative overdraft.

Three features of Figs. 2 and 3 illustrate the findings on the welfare effects across the four cases. One, in the initial stage of extraction, the groundwater pumping path when CAP is not built (NoBuild) is virtually indistinguishable from efficient groundwater extraction (Efficiency). The two cases begin to diverge after about 75 years, but then diverge markedly after CAP is constructed in $T = 123$ in the Efficiency case. Ultimately, the price is much higher in the NoBuild case because the case 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.

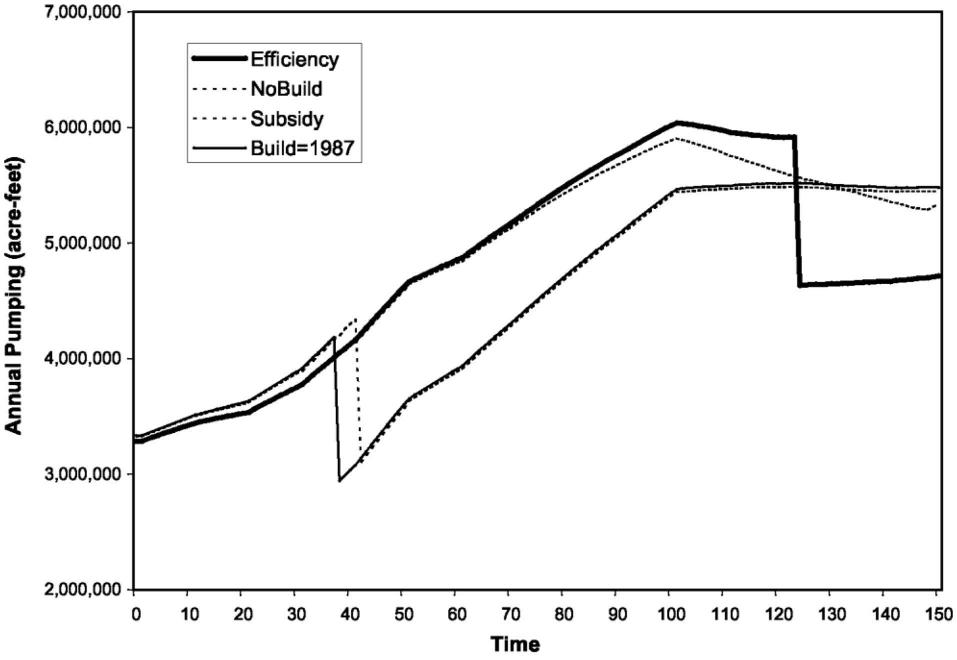


Fig. 2. Groundwater pumping, $q(t)$, through 150 years.

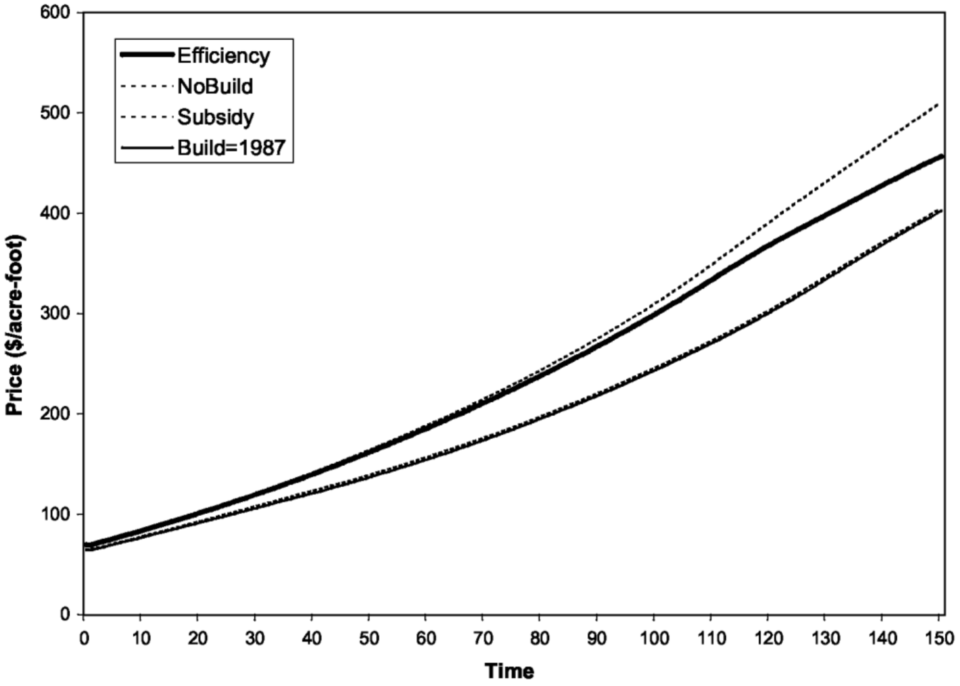


Fig. 3. Price path, $p(t)$, through 150 years.

Two, the efficient path mines significantly more groundwater between 1987 and 2073 than the cases in which CAP is built in 1987 or 1991 (the cases Build = 1987 and Subsidy). 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, too much groundwater is pumped only prior to CAP construction. After CAP construction, 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 2073, 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 1987 (Build = 1987) rather than 1991 (Subsidy) shows that, again, the increased inefficiency stems from importing expensive surface water too early (Fig. 2). The paths differ substantially only for the 4 years between 1987 and 1991, but otherwise are very similar. Despite this similarity, the deadweight loss decreases by $0.431 billion with the later construction date. Since the paths diverge relatively early in time, this minor difference in allocations translates into a more substantial welfare difference.[35]

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 US Congress when choosing between competing proposals for siting the aqueduct to central Arizona [33]. 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 1000 ft 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" [33, 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 $275.32 acre ft (Table 1). As noted above, the optimal solution to this problem generates welfare of $74.172 billion. The proposed northern route, in contrast, has construction costs of $8.009 billion and operating costs of $124.43 acre ft.[36] The optimal program under these conditions would build the project in 2055 and generate greater welfare, $74.266 billion. Thus, the political calculation that ultimately resulted in construction of the western route reduced the potential value of CAP by $94 million.[37]

6. A political exchange: CAP subsidies for reform of groundwater law

A primary political motivation for the construction of CAP was to reduce and, ultimately, eliminate groundwater mining. Policy makers knew, however, that CAP alone would not correct Arizona's perceived groundwater problem. Thus, the Arizona Groundwater Management Act of 1980 includes two major features: development of well-defined groundwater rights in place of common-property rights and a ban on groundwater mining beginning 2025.

6.1. Well-defined groundwater property rights

The prospective political exchange of CAP subsidies for groundwater reform forced Arizona to compare two possible outcomes: (1) building CAP in 1987 with groundwater rights defined under a new law versus (2) building CAP without subsidy but with groundwater rights defined as common property.[38] The former outcome is the Build = 1987 case of Section 5; the latter outcome is labeled ComProp. Arizona's preferred construction timing for CAP would be 2062 under the conditions of ComProp. This date is earlier than efficient timing because of myopic pumping, yet much later than the subsidized construction in 1987. Arizona clearly prefers Build = 1987 in light of the government subsidies; the net benefit to Arizona is $1.425 billion higher under Build = 1987 than ComProp (Table 3). Fig. 4 shows the groundwater pumping paths for the two outcomes. The myopic pumping of ComProp results in significantly greater pumping and overdraft relative to Build 1/4 1987.[39]

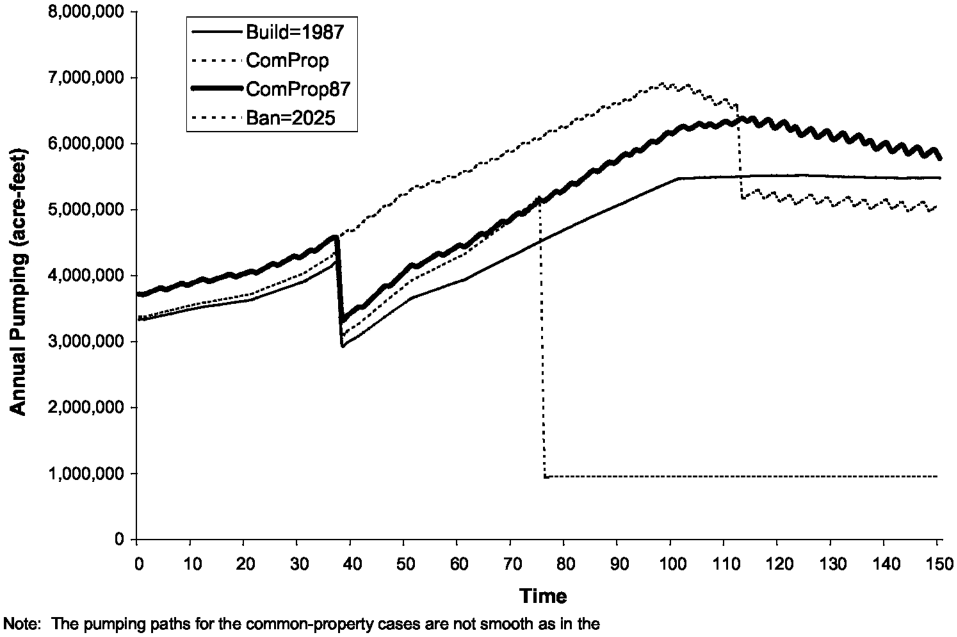
Was the political exchange—subsidies for legal reform—sound economic policy? Comparison of deadweight loss suggests not. The loss of Build = 1987 is $2.612 billion; the loss of ComProp is $0.8 10 billion.[40] The water-project subsidies introduced a larger inefficiency than was removed by the property-rights reform.[41]

Table 3
Political exchange: CAP subsidies for reform of groundwater law

Policy alternative	T	Welfare	Deadweight loss	Net benefit to Arizona
Build = 1987 case	37	$71.560 bill	$2.612 bill	$73.594 bill
ComProp case	112	$73.362 bill	$0.810 bill	$72.169 bill
ComPrp87 case	37	$70.944 bill	$3.228 bill	$72.978 bill
Ban = 2025 case	37	$68.020 bill	$6.151 bill	$70.054 bill

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

A narrower perspective on the political exchange relates to the federal government's 1979 decision to enforce the federal requirement for state groundwater reform. If we take the 1987 construction date as given, what are the consequences of federal enforcement? Without enforcement, common-pool depletion of groundwater and CAP construction in 1987 (labeled ComPrp87) result in a deadweight loss of $3.228 billion (Table 3). With enforcement, well-defined groundwater rights and CAP construction in 1987 result in a deadweight loss of $2.612 billion. Thus, a substantial return accrues to the well-defined groundwater rights, $0.616 billion. From this perspective, the federal government avoided a worse outcome of subsidizing, building in 1987, and not enforcing the requirement for reform.



Note: The pumping paths for the common-property cases are not smooth as in the other paths because the (positive) shadow values smooth extraction in the other cases.

Fig. 4. Groundwater pumping, $q(t)$, through 150 years; the effect of groundwater laws.

6.2. The ban on groundwater mining after 2025

The ban on groundwater mining is scheduled to begin 1 January 2025. The ban would force groundwater pumping to a steady-state centuries before a steady-state would be reached if pumpers were allowed to pump freely (either with well-defined or common-property rights) (Fig. 4). The ban in 2025 (denoted Ban = 2025) is assessed while fixing the CAP construction date at 1987 and extracting groundwater with well-defined property rights. Over 900 million acre ft of groundwater that are pumped without the ban remain in the aquifer with the ban. Imposing such a constraint would be clearly harmful: the ban results in a deadweight loss of $6.151 billion (Table 3).

Note that groundwater pumping prior to 2025 increases in response to the ban.[42] Beginning from the initial date, groundwater pumping with the 2025 ban exceeds pumping without the ban (i.e., in Build = 1987 with well-defined groundwater rights, CAP construction in 1987, and no ban). The difference grows over time until, in 2024, over 5.1 million acre ft is pumped under the ban compared to roughly 4.5 million acre ft without the ban

(Ban = 2025 versus Build = 1987 in Fig. 4). Thus, the ban produces two effects: too much groundwater pumping before the ban and too little pumping after the ban.[43]

Two factors—the relatively large deadweight loss and the prospect of distributing the ban's artificial scarcity—raise serious doubts about Arizona's willingness to enforce the ban. The deadweight loss of $6.151 billion is substantially larger than the deadweight loss from the comparable case, Build = 1987, with its deadweight loss of $2.612 billion. Moreover, groundwater pumping would decrease abruptly after the ban, with a reduction of over 4.2 million acre ft in 2025. How would this artificial scarcity be distributed? It is unclear. Given these factors, economic and political pressure to remove or delay the ban will likely increase as 2025 approaches.

7. Conclusion

In Cadillac Desert, Reisner presents ample anecdotal and historical evidence to argue that water project development in the American West was financially extravagant and wasteful of water resources. In this paper, we develop a model of the dynamic tradeoff between water project construction and groundwater mining that incorporates a project's setup costs and capacity constraint. Using the model, we find strong support for Reisner's thesis by quantifying the inefficiencies of water use in Arizona. First, CAP should have been built in 2073, over eight decades later than the actual construction date. Second, we find a relatively small increment to social surplus from constructing CAP: $95 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: $2.612 billion. We reach a stark conclusion: building CAP in 1987 was worse than never building CAP at all.

Arizona's perspective on CAP reflects the distortions of public policy and insecure property rights. Arizona could have implemented the efficient program of groundwater mining and CAP timing. Instead, it pressed for early construction of CAP by the federal government. Federal subsidy of CAP provided strong incentive for early construction. In addition, Arizona's property right to Colorado River water was insecure prior to CAP construction; Arizona received no value from this water prior to CAP. Relative to efficient timing, Arizona received a net benefit of almost $1 billion from CAP's completion in 1987. The 1987 date is quite similar to Arizona's preferred date of 199 1.

With CAP, the federal government introduced a new strategy of trading a subsidized project for state groundwater reform. This strategy produced bad policy in the Arizona case. We estimate that common-pool extraction yields a deadweight loss of $0.810 billion. Because CAP subsidies create a greater inefficiency, trading CAP subsidies for groundwater reform resulted in a net cost of $1.802 billion. 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] Our analysis suggests that a better recommendation is that water-import projects simply should not be subsidized.

Appendix A. Simulation model parameters

The appendix documents the information sources for the simulation model's parameters (Table 1). The procedures underlying parameter development are available from the authors.

Aggregate water demand: Water demand equations are constructed from estimates of the price elasticity of demand and data on water prices and quantities. The study uses elasticities of —0.624 for the municipal and industrial sector and —0. 178 for the agricultural sector. Information sources for construction of the demand functions include: [1,2,4,6,47–50].

Central Arizona Project: The annual CAP quantity delivered is the mean of the projected deliveries for the period 1998–2046 [51]. The unsubsidized setup cost is the present value of actual and projected CAP construction expenditures from 1972–2002 [51]. The figure also includes capital expenditures on distribution systems from the CAP aqueduct to retail water districts [58]. Subsidized setup cost consists of the legally required repayment of CAP construction expenditures [51]. Computations of subsidized setup costs also incorporate interest-free loans made to retail water districts for distribution systems [58].

Unsubsidized operating cost has three components: (1) an unsubsidized electricity cost for pumping water through the CAP system [51,9], (2) observed CAP operating costs (other than those related to electricity) [51], and (3) projected operating costs of transporting water from the CAP aqueduct to retail water consumers [15]. In contrast, subsidized operating cost for CAP water involves charges actually levied on CAP customers by the Central Arizona Water Conservation District [16]. The positive opportunity cost for CAP water applies the market-clearing price from a simulated Colorado River market [9], converted from an in-river price to a central Arizona price.

Central Arizona aquifer model: Parameters for the central Arizona aquifer model are developed from publications of the US Geological Survey [52–54] and central Arizona planning documents [6].

Groundwater pumping cost: Based on Bush and Martin [15], the long-run marginal pumping cost is $0.179/ acre ft per foot of lift with an additional fixed charge of $4.235/acre ft. For example, the cost of pumping 1 acre ft of water 1000 ft is $183.24. The energy component of pumping cost incorporates a Booker and Young [9] electricity cost estimate and an additional electricity "distribution delivery charge" applied by the Salt River Project [44].

Local surface water supply: Arizona planning documents [6] report average water supply by the local rivers of central Arizona. We use the 1980 price charged by the Salt River Project in central Arizona [41] as this water's unit cost.

Interest rate: The interest/discount rate is the average annual real rate for 1972–1997 [19].

Notes:

[1] Groundwater mining is defined as the pumping of groundwater at a rate faster than the rate of recharge.

2 While the analysis focuses on the western United States, the methodology has application in other regions. An ambitious proposal in China, for example, would import water to northern China from the Yangtze River basin in southern China [40]. The project, estimated to cost $30 billion, would provide water in part to substitute for nonrenewable groundwater reserves in the north.

3 Some elements of this framework were developed earlier for the case of groundwater depletion and surface-water imports [12,17,34].

4 Setup costs create a nonconvexity in the production possibilities set, which leads to the nonexistence of a competitive equilibrium in the exhaustible resource problem [26]. However, adding a flow capacity constraint in addition to setup costs results in conditions under which existence of a competitive equilibrium is preserved [29]. See Amigues et al. [3] for analysis of a general equilibrium model of resource depletion with a capacity-constrained backstop and Kim and Moore [34] or Holland [28] for similar partial equilibrium analyses.

5 Many of the largest federal water projects (both actual and proposed) involved interbasin water transfers as "rescue operations" for regions that were exhausting local groundwater supplies [32]. 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 [57].

6 A series of studies coauthored by William E. Martin (e.g., [15,33]) made the point that groundwater would be cheaper than CAP water if CAP construction was timed as planned. Our study is the first to assess optimal CAP timing and the deadweight loss of inefficient policies.

7 The Reclamation program recorded impressive statistics: construction of 355 storage reservoirs, 255 diversion dams, and 18, 000 miles of water-transport facilities. Historians aptly refer to the program with evocative phrases, such as Reisner's Cadillac Desert and Worster's Rivers of Empire.

8 In 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 [59].

9 Sax et al. [45, 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.”

10An early proposal for intrastate marketing of Colorado River water examined potential gains from trade in southern California [46].

11 Sax et al. [45, 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.”

12 Water “used” refers to gross water usage since recharge to the aquifer from percolation is modeled explicitly.

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

14 Alternatively, $\bar{I}$ could represent the capacity of the water project and I the quantity of water transported by the project. With constant marginal costs, the project will always be used to capacity once it is constructed.

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

16 The recharge, R, is assumed to be nonstochastic. 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.

17 For tractability, the model assumes instantaneous recharge. In practice, recharge does not occur instantly in aquifer systems.

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

19 The model could be extended to include costs of subsidence by including an additional cost term. Subsidence cost is a function of cumulative overdraft and affects the shadow value of the groundwater.

20 If construction costs are greater than the surplus from the project, then it is not efficient to build the water project. Furthermore, if the operating cost of importing water is high, then the project may not be used to capacity. With the parameters of this study, it is efficient to build the project and import water at capacity.

21 Alternatively, we can think of $(1 — \alpha)\lambda(t)$ as the scarcity cost of pumping a unit of groundwater, since the fraction α returns to the aquifer. Eq. (2) then equates marginal social benefit with marginal social cost.

22As 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 $\dot{p}(\mathrm{t}) = c'(S)[-R - \alpha(L + I)] + r\lambda(t)(1 - \alpha) > 0$. This holds if the increase in the marginal pumping cost is small as cumulative overdraft increases.

23 Due to the nonconvex production sets (caused by the setup 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.

24Note 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.

25 The comparative static result follows because the initial price, $p(0)$, must be lower which then implies that the project must be constructed earlier.

26 The subsidies and ban do not change usage on the margin since the first-order conditions (Eqs. (2) and (3)) do not directly depend on the setup and operating costs. The subsidies and ban also do not affect steady-state water usage and pumping. Thus, if the federal government mandated the construction date, the project planner would operate the project efficiently.

27 An alternative approach would be to solve the common-pool extraction game for a finite number of pumpers. However, Brooks et al. [10] 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.

28 Water conservation programs pursued by various Arizona utilities may shift per capita demand. Modeling these conservation programs would reinforce our results by implying CAP should be constructed even later.

29 CAP water tends to be poorer quality (in terms of salinity) than groundwater in central Arizona [15]. We only analyze water-quantity tradeoffs, however, not quality tradeoffs.

30 Without the CAP, efficient groundwater mining continues to a pumping height of 8236 ft as opposed to a maximum pumping height of 6215 if CAP is constructed. Hydrologic investigations find that central Arizona's groundwater basins regularly approach or exceed 10, 000 ft in saturated thickness [5,53]. Nevertheless, earlier runs of the model suggested that the results were not sensitive to the assumption about groundwater availability at large pumping heights. In general, pumping at great depth contributes little surplus because the marginal value of the water is close to the pumping cost.

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

32 Howe [3 1] makes the general point that federal subsidy of water projects commonly creates conflicting perspectives between regional and national interests. He cites several examples in which regional beneficiaries advocate projects with negative social net benefits.

33 Although we graph outcomes through 150 years, steady states are reached after 700 years in these cases. Note also that, during the first 150 years, groundwater pumping height begins at 88 ft and increases to between 1654 ft (Build = 1987 case) and 2146 ft (NoBuild case) at $t = 150$.

34 The efficient price grows over time, from $p(0)$ = \$69.72 to $p(T)$ = \$381.19 to $p(T^{ss})$ = \$1142.87. Note that as in Eq. (3), the growth rate of the efficient price is less than the interest rate.

35 A sensitivity analysis of several parameters shows that the qualitative results reported here are valid for a wide range of parameters. However, the numerical results are sensitive to the discount rate as would be expected.

36 A 1947 Reclamation study finds that construction costs for the northern route are \$400 million higher than the western route [33]. 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.

37 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 1940s. In the 1960s, 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" [42, p. 295].

38 Arizona's construction of CAP without federal subsidy was a realistic alternative. According to Ingram et al. [33, 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."

39As discussed in Section 3, the steady-state pumping height is lower for the efficient case relative to the common-property case since myopic pumpers do not consider the effect of current pumping on the steady-state pumping cost. According to the model, the efficient steady-state height is 1538 ft, while the common-property steady-state height is 1611 ft.

40 The deadweight loss under ComProp is 1.1% of welfare. Research on New Mexico and Texas aquifers found the value of groundwater management to be less than 1% of welfare [24,35]. Feinerman and Knapp [20] 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.

42This empirical finding is consistent with Long's [37] theoretical result showing that a resource will be extracted at a faster rate if it is to be nationalized at a known future date. Lee [36] derives a similar result for a price ceiling for a nonrenewable resource that is binding in the future.

43 We model the ban as an abrupt cessation of groundwater mining in 2025. The Groundwater Management Act of 1980 attempts to legislate a gradual decrease in the rate of groundwater mining prior to the ban. This would produce a larger deadweight loss than our estimates since even more valuable groundwater would remain unpumped.

44The 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" [57, pp. 6–23].

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