The role for policy in common pool groundwater use

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Received 4 February 1999; received in revised form 18 August 1999; accepted 2 December 1999

Abstract

We consider a model of intertemporal common pool groundwater use with substitutable irrigation technology and declining yields from groundwater stocks where pumping cost/stock externalities arise from the usual common property problem. We contrast competitive and optimal allocations and examine the role of substitutable irrigation capital vis-a-vis the effectuation of efficient methods as well as levels of resource use. A case study involving groundwater use in New Mexico illustrates the procedures and considers the efficacy of some simple policy options regarding the amelioration of inefficiencies. © 2001 Elsevier Science B.V. All rights reserved.

JEL classification: C61; Q25; D92

Keywords: Optimal control; Water; Common property; Irrigation

1. Introduction

The rapid development of large-scale irrigated agriculture in the Southwestern United States created heavy demands on limited groundwater supplies. By 1970 it appeared that groundwater supplies were threatened in some areas, leading to heightened public concern as well as professional debate regarding this issue. At the heart of this debate is the question concerning the extent to which externalities in groundwater pumping — common property problems, pumping cost externalities and the concomitant failure to consider the opportunity cost of currently consumed groundwater stocks — might have a significant quantitative effect on the deviation between competitive and socially optimal rates of groundwater pumping; i.e., it is well known that externalities in groundwater pumping and common property problems would generally lead to a qualitative acceleration of groundwater exploitation as a result of following competitive vis-a-vis socially optimal pumping rules; however, it is the quantitative deviation in these pumping rates that defines the potential role of water
management policy in this context. A derivative issue concerns the extent to which potential policy gains can be captured by viable policy instruments.

2. Background and overview

The initial attempts to address the issue concerning the actual divergence of optimal and competitive plans appeared in Gisser and Sanchez (1980) in the context of a case study of the Pecos, a confined aquifer in New Mexico. This study undertook a qualitative comparison of alternative quantitative pumping schedules wherein actual schedules were calculated for competitive and optimal water pumping but comparison was limited to an intra ocular trauma test. Subsequent studies employed aggregate measures of the discounted present value of the stream of net private returns to compare the results of competitive vs. socially optimal use of groundwater supplies (see, e.g., Feinerman and Knapp, 1983; Nieswiadomy, 1985; Kim et al., 1989; Brill and Burness, 1994; Knapp and Olson, 1995). These studies provide an alternative basis for quantifying inefficiencies in water use, but simultaneously introduce biases common to measures which discount future values (see Page, 1977a,b).

The problem of identifying and quantifying these inefficiencies in water use is confounded by other considerations as well. As the literature has expanded over time, so has the taxonomy regarding what is included in the “externalities” associated with common pool resources. Negri (1989) augments the externality concept to include gaming considerations due to restricted access to the resource while Provencher and Burt (1993) introduce the possibility of an additional externality when users are risk averse. As the taxonomy of externality in this context burgeoned, so did the range of behavior that might be considered under the umbrella of “competition” or, more appropriately, “equilibrium.” Negri (1989) refines the equilibrium notion to include Nash decision strategies while Provencher and Burt (1993) introduce similar refinements arising from uncertain income streams. These considerations constitute substitute bases for qualitative deviations between optimal and “equilibrium” plans and simultaneously raise concomitant questions concerning the extent to which the deviations are significant in some quantitative sense. We limit our analysis to the classic common pool problem and ignore these refinements. As our solutions paths tend to provide bounds for these refinements, the results of our empirical investigations may provide some insight regarding the quantitative relevance of these alternative paradigms.  

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1 These studies, for the most part, find little difference between competitive and optimal resource use based on present value measures. Brill and Burness (1994) present an exception to this pattern.

2 For a lucid taxonomy of various externalities that might attend a common property resource, see Provencher and Burt (1993).

3 In the current context the basis for these refinement is the restricted access nature of the common property resource. The literature on this goes back to Levhari and Mirman (1982), Eswaren and Lewis (1984), Reinganum and Stokey (1985) and Bolle (1986) who all restrict their analyses to specific functional forms, and, more recently, Karp (1992), who uses the more general methods of Clemhout and Wan (1985) and van der Ploeg (1987), but extends their analyses to consider the entire equilibrium trajectory as opposed to only steady states. Interestingly, Karp concludes on the basis of his numerical simulation of closed loop restricted access systems: “The welfare comparisons are quite insensitive to the number of firms when the number exceeds 8” and “these simulations suggest: The open-access model is likely to provide a reasonably close approximation to a common property oligopoly when there are more than several firms” (Karp, 1992, pp. 363–364). Additionally, Chermak and Krause (1999) explore the extent of selfish versus altruistic behavior in an experimental setting.
Our analysis is couched in the context of a dynamic model of common property groundwater resource use with pumping cost/stock externalities; specifically, it incorporates (a) declining yields from groundwater stocks, and (b) endogenous investment in irrigation technology so as to focus on the nature of the long run trade-off between increased pumping costs from declining aquifer yield and the increased benefits associated with more efficient irrigation technologies. Consequently, our analysis is concerned with efficient methods as well as levels of resource use.

Declining well yields tend to exacerbate the difference between competitive and optimal patterns of water use (Brill and Burness, 1994) while the adoption of more water efficient irrigation technologies might appear to ameliorate this difference, thus seemingly delineating the tradeoff. However, in response to policy implementation, these substitution possibilities may tend to hinder the effectiveness of policies intended to remedy inefficiencies in water use. We explore the extent to which potential policy gains are affected by these considerations or, more explicitly, the extent to which substitute inputs provide incentives that tend to defeat policies intended to capture potential surplus.

The model is specified under fairly palatable conditions that allow an extension of the Just–Hueth (1979) result so that farm revenues can be expressed solely as a function of the marginal revenue product of water even though other variable inputs are utilized. This procedure circumvents some problems of data availability in the numerical analysis and, in particular, obviates the need to estimate the demand for (irrigation) capital. In addition, the analysis employs an alternative procedure for generating water-pumping data when direct observations on water pumping are not available. The general model is applied to a case study in eastern New Mexico so as to generate numerical results.

3. The model

We adapt the notion of application efficiency utilized by Caswell and Zilberman (1986), extending it so as include continuously malleable irrigation capital and suppressing the land-quality aspect of their definition in order to focus more closely on the investment/conservation trade-off. Increased application efficiency causes an upward shift of the benefit function, which is offset to some extent by increased capital costs. We employ the Sloggett and Mapp (1984) specification of declining well yield function so that the marginal pumping cost is shifted upward more than proportionately to increase lift as the water table falls.

We suppress inputs other than irrigation capital and water in order to highlight the effects of the irrigation investment/pumping cost dichotomy alluded to above. The model is intentionally fairly spartan in terms of its hydrological and agronomic specification; e.g.,

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4 A reviewer has pointed out that “competitive” behavior need not be “myopic.” We concur. The problem is not with the market mechanism, but the property rights institution. However, this misuse seems to be fairly commonplace, so we will not interfere with its perpetuation and hope that readers will suffer this imprecision.

5 In an inquiry somewhat related to Caswell and Zilberman, Knapp et al. (1990) consider the trade-off between investment in irrigation technology, which reduces the amount of water that percolates below the root system, and drainage technology, which limits reductions in yield resulting from inadequate drainage.

6 Shah et al. (1993, 1995) consider a dynamic extension of the Caswell and Zilberman model to the case of groundwater pumping; in their model investment in irrigation technology is land quality augmenting.
we abstract from most site-specific characteristics of agricultural water use — such as soil and slope conditions, crop mix, etc. — and, in addition, ignore hydrological considerations such as finite hydraulic conductivity, base flow, stochastic recharge, etc. However, sensitivity analyses and extensions of the basic model indicate that the inclusion of many of these considerations has little quantitative effect on the results we adduce (Burness and Brill, 1992).

3.1. Application efficiency.

Application efficiency is defined as the ratio of crop water requirements to water applied per acre. For a given crop mix, crop water requirements (at the root zone of the crop) are assumed to be fixed, while the amount of water that must be applied in order to meet these crop requirements is an inverse function of investment in irrigation technology (Blaney and Hanson, 1965). We summarize this in the water accounting identity that defines application efficiency as

\[ e(k) = \frac{C_R A}{w} \]  

(1)

where \( w \) is water pumped or applied water in acre-feet (AF), \( C_R \) is crop requirements (AF/A), \( A \) is irrigated acres (A), \( e(k) \) is application efficiency (percentage), and \( k \) is investment in irrigation technology (US$/A). For \( 0 \leq e(k) \leq 1 \), we would generally expect \( \frac{de}{dk} \geq 0 \) and \( d^2e/d^2k \leq 0 \) among non-dominated irrigation technologies. \( C_R A = e(k)w \) is water consumed by crops or effective water; thus, the ratio of effective water to applied water determines application efficiency. With increased investment in irrigation technology the amount of applied water required to meet plant needs falls and application efficiency increases.

3.2. Capital cost

Application efficiency is defined by investment or capital stock per irrigated acre; consequently, capital costs must be tied to investment per acre as well. The capital stock is \( K = kA \) where \( k \) is capital per acre and \( A \) is irrigated acres. From the identity (1) above, we have \( A = e(k)w/C_R \), so that \( K = ke(k)w/C_R \). If the rental rate on capital \( r \) and operation and maintenance costs are \( \delta K \), then total annual capital costs are \( (r + \delta)K = \eta ke(k)w \) where \( \eta = (r + \delta)/C_R \).

3.3. Pumping cost with declining well yield

Continued pumping decreases the saturated thickness of the aquifer causing well yields to fall. In order to quantify this phenomenon, we use the well yield function proposed by

\[ \text{This follows Caswell and Zilberman (1986). However, in some cases, efficiency may be tied to aggregate capital such as in the case of district wide facilities such as central irrigation canals or storage systems although one could argue that these are related to distribution as opposed to application. However, in our context (individual farm pumping from groundwater stocks), these are not relevant.} \]

\[ \text{Our formulation admittedly ignores some of the richness associated with lumpy capital and non-trivial adjustment costs. However, we employ the simpler formulation so as to focus on the long-term aggregate aspects of comparative water use possibilities. Additionally, as application efficiency and hence production are tied to capital per acre, considering capital as continuously variable and free of adjustment costs simplifies the analytics.} \]
Sloggett and Mapp (1984); well yield (AF/h) is \( Y = 2Q_0[h(H(t) - H_c - d/2)] \) where \( H(t) \) is the height of water table (above the reference plane) at time \( t \), \( H_c \) is the height of aquifer bottom, \( d \) is drawdown, and \( Q_0 \) is a constant depending on aquifer permeability, well radius and the radius of the cone of depression.

Unit (marginal) pumping costs are \( \frac{C(H)}{Y} = C_0(S_L - H(t))(S_L - H_0)/Y \) where \( S_L \) is the height of the surface level, \( H_0 \) is the initial height of the water table and \( C_0 \) is the hourly cost of running the pump at the initial lift level and \( Y \) is well yield as given above. Thus, the unit cost of pumping is the hourly cost of operating the pump for a specified lift \( (C_0) \) multiplied by the relative lift \( ((S_L - H(t))/(S_L - H_0)) \) and divided by the well yield \( (Y) \) for that lift in acre-feet per hour yielding cost per acre foot for any specified lift.

As the water table level falls, unit pumping costs (US$/AF) increase due to (i) increased pump lifts to the surface and, in addition, (ii) reduced well yield (from decreased saturated thickness). The implication of decreasing well yield may be consequential as generally with declining well yield economic depletion occurs before physical depletion so that at the steady state there may be significant stocks of water remaining.9

3.4. Net farm benefits

Following Kim et al. (1989), net farm benefits are defined as the area under the value of marginal product curves minus pumping and capital costs at each point in time. The tacit argument seems to be that the study areas concerned are a small part of the overall market, so that consumer surplus measures can be ignored and benefit calculations can be limited to those generated in the input markets. Using (1), we define the farm’s production function as \( Q_D(\text{F}(\text{e}(k),w)) \) so that output, \( Q \), is a function of effective water, \( e(k)w \). We assume that \( \text{F}(\cdot) \) is monotonic increasing and concave. From static profit maximization, the inverse factor demands (VMP schedules) for water and capital, denoted \( p(w,k) \) and \( q(w,k) \), respectively, can be obtained.

We assume that irrigation water is a “weakly essential” input; i.e., water is an essential input at the margin or, more specifically, that the VMP of capital is zero when water input is zero. Overall, this seems to be a fairly palatable assumption, as it means that adopting a more advanced irrigation technology results in no additional output when water input is

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9 While the assumption of constant well yield does not universally lead to physical exhaustion, it often does, whereas the assumption of declining well yields generally implies that physical depletion will not occur. As a practical matter physical depletion of aquifer stocks is impossible as overpumping and subsequent reduction of saturated thickness below certain critical levels can precipitate irreversible aquifer damage. Moreover, in practice irregular aquifer bottoms may lead to sporadic loss of wells over time through exploitation (see Lansford et al., 1982; Tsur and Zemel, 1995). In a somewhat related investigation, Worthington et al. (1985) consider a confined aquifer and examine the tradeoff between the maintenance of Artesian pressure and pumping lifts/costs. In particular, they note that excessive pumping may transform the aquifer from a confined to unconfined status.

10 This is a basic extension of a result by Just and Hueth (1979) which assumes “essential” inputs; an essential input is one for which output is zero whenever that input is zero. The less restrictive assumption of “weakly essential” inputs allows (but does not require) that \( \text{F}(0) \) is non-zero. Empirically there is mixed evidence as to whether \( \text{F}(0) \) is non-zero, but generally the intercept term seems to be fairly small (see Kallsen et al., 1981 or Sammis and Guitar, 1981).
zero. Given this assumption, farm revenues attributable to irrigation water and irrigation capital are (see Appendix A)

\[ R(e(k)w) = \int_0^w p(z, k)dz \]

Thus, net farm benefits, or quasi-rents, from variable factors at time \( t \) (suppressed) are

\[ B = R(e(k)w) - C(H)w - \eta e(k)wk \]

3.5. All together now

The economic model outlined above is conjoined with a hydrological model along with relevant institutional specifications. We consider a single-cell, unconfined aquifer in which the change in the water table is defined by

\[ \dot{H} = \frac{1}{A_S} [N + (\alpha(k) - 1)w], \quad H(0) = H_0, \quad H(T) \geq H_c \]

where \( A_S \) is the surface area of the land overlying the aquifer times the specific yield, \( N \) is natural recharge, and \( 0 < \alpha(k) < 1 \) is the return flow coefficient, which is technology-dependent with \( d\alpha(k)/dk < 0 \).

We consider two alternative institutional regimes: planning and competitive. The planning problem requires maximization of the discounted present value of net farm returns subject to the constraint (2); i.e., the planning problem makes full allowance for the common pool externalities and hence describes the socially optimal exploitation of the aquifer. In the competitive solution individuals maximize the discounted present value of net farm returns while ignoring the effect of current actions on future alternatives.

Incorporating earlier discussions, the discounted present value of farm benefits can be written as

\[ V = \int_0^T e^{-rt}B(t)dt = \int_0^T e^{-rt}[R(e(k)w) - C(H)w - \eta e(k)wk]dt \]

Thus, for the planning solution (3) is maximized subject to (2). Necessary conditions

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11 Only one obvious exception comes to mind, the case of furrow diking, in which case more effective use is made of both rainfall and irrigation water.
12 Marshall (1924) defines quasi-rents as the returns to the variable factors of production (irrigation capital and water in our case). Since net farm benefits or profits equal quasi-rents plus fixed costs, maximizing one is equivalent to maximizing the other; hence we often use these terms interchangeably for simplicity in exposition. The quasi-rent measure is employed as a decision objective in contexts similar to ours by numerous other authors (except they have only water as a variable input) (see Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Nieswiadomy, 1985; Kim et al., 1989).
13 The control variables are pumped water \( (w) \) and capital per irrigated acre \( (k) \). The choice of a \((w,k)\) combination determines irrigated acreage according to Eq. (1). In the context of our model with declining well yields, corner solutions would seem to be somewhat pathological (for example, in the case where overpumping might result in aquifer collapse), so we restrict our analysis to interior solutions wherein \( w > 0 \) and \( k > 0 \). Of course, while the necessary conditions are stated for interior solutions, this in no way precludes corner solutions from the numerical analysis.
require that the current value Hamiltonian
\[ H = R(e(k)w) - C(H)w - \eta e(k)wk + \mu[N + (\alpha(k) - 1)w]/A_S \] (4)
is maximized for all \( t \). At an interior solution this yields
\[ R'(e(k)w)e(k) - C(H) - \eta e(k)k + \mu(\alpha(k) - 1)/A_S = 0 \] (5a)
\[ R'(e(k)w)e'(k) - \eta e'(k)k + e(k)) + \mu \alpha'(k)w/A_S = 0 \] (5b)
\[ \mu - r \mu = C'(H)w \] (5c)
where primes denote differentiation and \( \alpha'(k) < 0 \). The multiplier \( \mu \) is the current value marginal user cost of water.

In the competitive case, since irrigators behave as if they are ignorant of the effects of their decisions on future water availability and hence maximize the discounted present value of net farm benefits as given by (3) whilst neglecting the constraint (2). This is tantamount to myopically maximizing net farm benefits \( (B) \) at each point in time. As the constraint (2) is ignored, the conditions for an interior solution are
\[ R'(e(k)w)e(k) - C(H) - \eta e(k)k = 0 \] (6a)
\[ R'(e(k)w)e'(k) - \eta e'(k)k + e(k)) = 0 \] (6b)

Comparing the two sets of necessary conditions, the planning solution requires that net marginal water benefits be set equal to the shadow value of net water pumped (5a) and that net marginal capital benefits be set equal to the shadow value of water lost through additional investment (5b). Eq. (5c) describes the time path of the scarcity value or marginal user cost of water. The planning solution is obtained in the usual fashion using Eqs. (5a), (5b), (5c) and (2) along with boundary conditions.

For the competitive solution, net marginal water benefits and net marginal capital benefits are both set equal to zero ((6a) and (6b), respectively), i.e., water is pumped and capital is employed until no further current benefits are obtainable; the effect of these decisions on future water availability and pumping costs is ignored. The competitive solution is obtained by using Eqs. (6a) and (6b) to get \( w(H(t)) \) and \( k(H(t)) \), substituting these in (2) and solving.

4. Numerical analysis

We apply the model to Curry county, NM, an area that is fairly characteristic of irrigated agriculture in the Southern Ogallala in terms of crop mix, depth to groundwater,

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14 More explicitly, an additional dollar of investment, while directly affecting quasi-rents through the benefit function also has indirect effects through reductions in return flows (since \( \alpha'(k) < 0 \); if return flow were independent of irrigation technology, then net marginal capital benefits would be set equal to zero. However, this would not necessarily imply efficient levels of investment in irrigation technology as the numerical results will demonstrate.

15 Burness and Brill (1992) and (1994) consider a five-county area including Curry county adapting the demand relationship from Nieswiadomy (1985). Due to data availability and varying hydrologic considerations, the current analysis is more appropriately limited to Curry county. Curry county accounts for over half the pumping from the five-county area. The number of irrigators appears adequate to sustain the common property paradigm (see 3 supra, particularly the comments by Karp, 1992).
natural recharge, and return flow. The area is fairly similar to the Texas High Plans in soil and hydrological conditions. Curry county was subjected to intense groundwater development in the 1950s and 1960s and experienced a rapid decline in groundwater levels. As a consequence, questions concerning premature depletion of the groundwater stock arose and stimulated research concerning projected and appropriate rates of water usage (see, e.g., Lansford et al., 1982).

4.1. Parameter values

The parameter values are displayed in Table 1. Generally, the physical data were obtained from the New Mexico State Engineer’s Office and the study by Lansford et al. (1982). Cost, efficiency and return flow data were obtained from Amousson (1991) and Wyatt (1991). The efficiency function was fitted according to
\[ e(k) = 1 - \hat{e}_1 \exp(-\hat{e}_2 k). \]

The specific fitted efficiency function used is
\[ e(k) = 1 - 0.511 e^{-0.00744 k} \]
where \( k \) is 1990 US$/acre. The baseline data points were surge flow \( (e = 0.70 \text{ at US$72/acre}) \) and Low Energy Precision Application Systems (LEPA) \( (e = 0.95 \text{ at US$312/acre}) \); other technologies such as sideroll and center pivot sprinkler were dominated on a cost/efficiency basis by the surge flow or LEPA technologies or some convex combination thereof. For return flows in the range of observed contemporary irrigation efficiencies, the return flow function was fitted according to the relation
\[ \alpha(k) = \hat{\alpha}_1 \exp(-\hat{\alpha}_2 k). \]

The specific return flow function is \( \alpha(k) = 0.099 e^{-0.009 k} \). The return flow function nets out water losses (wind drift, etc.) which are treated as residuals. From

16 Linear, quadratic and exponential efficiency and return flow relations were considered. Within the first 50–80 years of model operation, all three of these performed roughly the same. The exponential form was finally selected as it was more tractable in the numerical analysis.
17 These systems use a low pressure spray from hoses dropped close to the plant height so that energy costs are reduced drastically concomitant with reductions in losses from wind drift. Efficiency is close to that of drip systems at about half the capital cost.
III-C, the pumping cost function is 
\[ C(H) = C_0(S_L - H)/(S_L - H_0) \times Q_0d(H - H_c - d/2) \] or numerically, 
\[ C(H) = \beta(4200 - H(t))/(H(T) - 3700) \] where \( \beta = \text{US}\$10.26/\text{AF (1990 US\$)} \).

4.2. Demand function

The variation in the demand for water as an input in agricultural production is explained by crop output price, rainfall, pumping cost, and irrigation technology. On the basis of the competitive assumption that price equals marginal cost, unit pumping cost is used as a proxy for the input price of water (see Nieswiadomy, 1985; Kim et al., 1989). Unfortunately, reliable data on water pumping are often not available. One received procedure for developing a water pumping series uses observed (changes in) water table levels to infer pumping levels via the transition Eq. (2) above (see Nieswiadomy, 1985). For our study area, accurate annual data for historical changes in the water table level was unavailable, hence we generated an alternative time series for pumping by using reported values for irrigated acreage with known values for efficiency and crop requirements and employing the water accounting identity (1) to generate the time series for pumping. This led to a much less variable time series for pumping.

For the time period 1958–1990, the demand for water for irrigated agriculture in Curry county, NM, was estimated as a lagged dependent variable model. A quantity-weighted crop output price was calculated using the four principle crops in Curry County — wheat, grain sorghum, corn, and cotton, which account for over 90% of the irrigated acreage. The empirical inverse demand function for irrigation water is (see Appendix B for detail)

\[ p(w, k) = 258.7e(k) - 0.001215[e(k)]^2w \]

4.3. Numerical solution

The models developed and specified above were validated vis-a-vis historical pumping for the study area and then solved numerically. The graphical representations of baseline results are presented in Figs. 1–5. Note that competitive pumping levels initially exceed those for the planning solution, but as the water table falls more rapidly under the competitive solution, the concomitant decrease in saturated thickness causes competitive pumping costs to rise more quickly, resulting in reduced pumping later in the program. As capital and water are substitutes in production, overpumping of groundwater results in underinvestment in irrigation technology for the competitive solution. In addition, effective water use is higher initially for the competitive solution; hence, via Eq. (1), irrigated acreage is initially larger as well. This observation highlights the inefficiency in the competitive solution as overpumping of water must outweigh the underinvestment in irrigation technology in order for irrigated acreage to increase. Similar to the pumping relationship, the investment (application efficiency) and irrigated acreage relationships reverse at about the 50-year point;

\[ \text{Following Sloggett and Mapp (1984, p. 232), } Q_0 = 0.0000164. \text{ Pumping costs are based on a pump with a capacity of 500 gpm (} Y_0 = 0.091827 \text{ AF/h) at an initial pumping depth of 300 ft with operating costs of US\$2.00/h.} \]

\( (S_L = 4200 \text{ ft, } H_0 = 3900 \text{ ft, } H_c = 3750 \text{ ft and } d = 20 \text{ ft yield the numerical pumping cost function in the text. This specification implies an initial pumping cost of roughly US\$22.00/AF.} \)
Fig. 1. Water level.

Fig. 2. Pumping.
Fig. 3. Efficiency.

Fig. 4. Irrigated acreage.
in particular, observe that early overpumping and underinvestment requires overinvestment in irrigation technology and less than optimal irrigated acreage late in the program when water becomes relatively scarce.

5. Policy analysis

In a somewhat different but related context, Burness and Brill (1992) evaluated a variety of policy instruments in order to determine their effectiveness in reducing efficiency losses; they considered the effects of direct controls on pumping, investment, or irrigated acreage as well as indirect policy instruments (such as water (pump) taxes, LEPA subsidies, interest rate subsidies) that alter the economic incentives facing the irrigator.19 We limit the discussion here to pump taxes.

As a point of departure, observe that the planning solution would be replicated exactly by imposing Pigouvian taxes defined implicitly by the multiplier terms in Eq. (4)

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19 The results concerning direct controls suggested that these policies were fairly effective but we omit them as we felt that the model was not sufficiently flexible to accurately reflect the effects of these instruments. In particular the effects of direct controls are introduced through the water accounting identity (1), but the fixed proportions relationship between water applied, effective water, irrigated acreage and crop requirements appeared to mask some of the substitution possibilities that one might expect in this context. The results concerning LEPA and interest rate subsidies suggested that these instruments were fairly ineffectual in altering patterns of water usage (see Burness and Brill, 1992).
above. In this particular application, the initial value of the Pigouvian tax on water (in excess of $21/AF) is roughly equal to initial pumping costs, raising serious questions concerning its feasibility with respect to its impacts on the agricultural sector. For this reason, and the fact that we wish to focus on policies that are less informationally demanding, we refrain from further discussion of Pigouvian taxes in favor of more operationally efficient alternatives.

We considered three different forms of a pump tax that have different incentive effects on water use: (i) a simple flat tax, which is constant over time, (ii) a neutral flat tax, which increases exponentially over time at the rate of interest, and (iii) a sliding-scale tax, for which the tax rate is a function of the irrigation technology employed. The most interesting of these taxes, both in terms of results and incentives, is the sliding scale tax. The sliding-scale tax, by tying the tax rate (inversely) to application efficiency, presents the irrigator with an incentive to decrease pumping in the face of a given tax or, alternatively, to invest in more efficient irrigation technology, thereby facing a lower tax rate and decreased water requirements, so that the tax is avoided to an extent on two counts.

A natural question arises concerning the manner in which the parameters of this tax function should be chosen. Feinerman and Knapp (1983) suggest as one possibility that tax receipts be rebated to users and the tax parameters chosen so as to maximize net social benefits including rebates. However, as they point out, in application the incentive effect of the tax may be lost if individuals perceive that on average they will be reimbursed for what they pay in taxes.

As an alternative, we propose an ad hoc method of choosing the tax parameters so as to: (i) keep the tax at a reasonably low level so as to minimize the negative effect on private returns; and (ii) generate a pumping schedule reasonably close to the planning schedule. This might be viewed as one possible second-best alternative to the Pigouvian solution defined in terms of the relative tradeoff between improved allocative efficiency and reductions in net private benefits and constrained by subjective notions of administrative and political feasibility.

Following these general guidelines we find that, as a rule, for both of the flat taxes, moderate levels of the tax are relatively ineffective in reducing pumping levels, and taxes sufficient to reduce pumping close to planning levels resulted in significant reductions in profitability. The best performance for the sliding-scale tax was obtained for a tax function

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20 The Pigouvian charges are directly related to $\mu$, the shadow value (or marginal user cost) of water per foot of aquifer thickness; the solution for $\mu$ is obtained from (5a), (5b), (5c). The tax rate per acre foot of pumped water is $-\mu(w-k) - 1)/A$ while the tax rate on irrigation capital $\mu w(k)/A$. At first blush, it may seem counter-intuitive to tax irrigation capital, as this would imply less reliance on water conserving technologies. However, as excessive levels of capital are utilized initially so as to help support the high levels of pumping associated with the competitive solution (see Figs. 2 and 3), these countervailing incentives are in order. Since competitors behave myopically, it suffices to focus on current incentives. Interestingly, the numerical solution supports the conjecture by Shah et al. (1993, 1995) concerning the inverted U-shape of the marginal user cost function; however, in our analysis the declining portion of the function did not begin until late in the time profile, much later than the 40-year policy horizon.

21 However, Feinerman and Knapp (1983) go on to observe that when the pump tax is tied to quantities pumped, rebates may not have this effect; they also observe that this is an empirical issue. Looking ahead, our results suggest that users tend to bear the tax burden much in excess of management gains.

22 Shah et al. (1993) suggest an alternative type of ad hoc procedure for constructing an irrigation technology-dependent tax function.
that started at about 25% of pumping costs. The ex ante tax function\textsuperscript{23} was designed to increase at 4% per year (so as to offset the effect of discounting) and so that an irrigator using LEPA technology would pay no tax.\textsuperscript{24} The ex post tax function started at US$5.50, rose slightly, then remained roughly constant until year 25 when it began a gradual decline to US$2.50 at year 40.

Solution time paths for the competitive problem when irrigators face this tax are illustrated in Figs. 6–10. Only the first 40 years are reported; this is consistent with long-range planning horizons or water plans employed by planning agencies (e.g., New Mexico State Engineer’s Office; High Plains Underground Water Conservation District No. 1 (TX)). Note that post-tax competitive pumping closely approximates the planning time path, especially during the early periods of pumping. The reduction in pumping is accompanied by an increase in initial application efficiency from 68% to 84%; substantial substitution of capital for water occurs ex ante before pumping commences. In the context of the model clearly the tax avoidance incentives for this tax are very strong. As a practical matter, one would expect this initial substitution of irrigation capital to be ameliorated to some extent by the costs of changing from one irrigation system to another. Moreover, on the positive side,

\textsuperscript{23} The “ex ante” tax function is the theoretical or functional form tax function. The “ex post” tax function is the empirical tax function reflecting the actual tax rate paid after users make optimal choices regarding irrigation technology.

\textsuperscript{24} The tax parameters were chosen through a grid search over parameter values with the tax functions evaluated in terms of objectives (i) and (ii) above. For taxes more punitive than the one chosen the reallocation effects in terms of water use were small compared to losses in post tax private benefits.
Fig. 7. Pumping.

Fig. 8. Efficiency.
Fig. 9. Irrigated acreage.

Fig. 10. Net private benefits.
the Texas High Plains Conservancy district reports considerable progress in overcoming resistance to adoption of the LEPA technology through a concerted effort to educate irrigators concerning irrigation technology investment costs. This suggests that the potential cost barriers in changing technologies may not impose a substantial impediment to the effective implementation of a sliding scale tax.

6. Summary of results

A priori we would expect, ceteris paribus, that the tendency for declining well yields to reduce the economically recoverable stock of water would exacerbate the differences between the competitive and planning solutions; i.e., the opportunity cost of water is greater and increases faster than in the case of constant well yields and competitive exploitation of water stocks ignores future and consider only current pumping costs. On the other hand, while endogenous irrigation capital does allow a more preferred class of pumping technologies for any given level of water pumping (which would tend to ameliorate the differences between the competitive and planning solutions), the fact that there is initial pretax under-investment in irrigation capacity suggests that irrigators further increase pumping, finding, at least initially, that it is cheaper to use less expensive irrigation technology and pump additional water. Of course, their perception of this as the least cost alternative is due to the fact that they ignore the opportunity costs associated with groundwater use.

The sliding tax provides irrigators with joint incentives to reduce water use and adopt more efficient irrigation technologies. As a consequence, pumping and irrigated acreage more closely approximate the planning solution, but there is a concomitant overinvestment in irrigation capacity early in the program. This switch from pretax underinvestment to posttax overinvestment in irrigation technology may precipitate countervailing incentives regarding efficient levels of water use. To some extent, this is manifested by greater use of effective water vis-a-vis the optimal solution; this follows directly from consideration of (1) above. However, (initial) effective water use falls relative to the pretax competitive (base case) solution.

We can also depict the effects of this policy in terms of present value calculations. As indicated above, we assume a 40-year policy horizon vis-a-vis the roughly 200-year horizon that characterizes the approach to the steady state. This is done partly in an attempt to mirror the planning horizons adopted by various water management agencies. We display present value measures in Table 2.

The present value measures reveal only a modest difference between the discounted present value of private benefits in the planning vis-a-vis the competitive solutions. The

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Discounted present values: net private benefits and net social benefits (million 1990 US$, r = 4%, 40-year policy horizon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning NPB (= NSB)</td>
<td>US$327</td>
</tr>
<tr>
<td>Competition (base case) NPB</td>
<td>US$320</td>
</tr>
<tr>
<td>Competition (sliding-scale tax) NPB</td>
<td>US$300</td>
</tr>
<tr>
<td>Competition (sliding-scale tax) NSB (NSB = NPB + tax collections)</td>
<td>US$323</td>
</tr>
</tbody>
</table>
benefit function, and hence the present value measures, collapse all efficiency gains and losses into a single metric over the relevant policy horizon, so that the welfare gains from more efficient water use are offset to some extent by inefficiencies in investment. As such, these present value measures seem to admit little scope for policy intended to ameliorate perceived inefficiencies in water use; that is, Table 2 suggests that the potential benefits from such policies, when evaluated in present value terms, is only on the order of US$7 million, the difference between the planning and competitive values. When contrasted with the graphical results concerning water usage (Fig. 7) and the time paths of benefits (Fig. 10) this seems somewhat paradoxical. Moreover, while the potential gains from policy are relatively small (US$7 million), the gains from policy are even more modest (on the order of US$3 million).

One possible implication of these results is that the economic benefits of regulating the resource are too small to justify such policies. However this need not be a foregone conclusion. To the extent that these implicit incongruities identified above are relevant, one might question the viability of present value measures in the context of such long-run policy considerations. In this regard, discounting has two interrelated effects (see Page, 1977a; or for a more popularized version, Page, 1977b). First discounting biases decision mechanisms toward the present. Second present value measures value resource utilization on the basis of the current generation’s preferences. The implications of the first effect may be unavoidable to the extent that they comprise an accurate behavioral description. The second observation may result in incomplete representation of the benefits attributable to various resource policies. In addition, short run policy horizons and periodic policy revision may tend to compound these biases.

However, these issues notwithstanding we observe whereas prior studies conclude that the quantitative divergence in competitive re optimal plans is dependent on aquifer characteristics (exogenous), the current effort ties this divergence as well to inputs (endogenous) that substitute for water; apparently, the endogeneity of substitutable inputs tends to frustrate policy attempts to internalize externalities associated with the common pool problem.

Acknowledgements

This research was financed in part by the U.S. Department of the Interior, Geological Survey, through the New Mexico Water Resources Research Institute. The authors also acknowledge helpful comments from David Brookshire, Jill Burness, Janie Chermak, Phil Ganderton, Kate Krause and Bob Patrick. Thanks are also due to several reviewers whose comments improved the exposition of this manuscript. The authors remain accountable.

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25 While we do not wish to enter the discounting debate as this has received substantial attention beginning with the intergenerational equity literature of the 1970s and resurfacing in the more recent literature on sustainable development, this is certainly an issue that warrants attention in the context of developing methodologies for evaluating the need and effectiveness of policy in the context of long-run analyses.
Appendix A. Benefit Function

The general result is that if all inputs are weakly essential (or, alternatively, essential at the margin), then quasi-revenues (revenues in the input markets attributable to the variable factors of production) are given by the area under any one of the VMP schedules (inverse factor demands); this is similar to a result of Just and Hueth (1979), but whereas they assume essential inputs (i.e., an input is essential if output is zero whenever that input is zero, or \( F(x_1, \ldots, x_{i-1}, 0, x_{i+1}, \ldots, x_n) = 0 \)), we require only that when input \( i \) is zero, the VMP for all other inputs should be zero. This condition is implied by but does not imply essential inputs and hence admits to a broader class of production functions with the possibility that \( F(0) \neq 0 \). A corollary to the general result is that if the \( k \)th input (only) is weakly essential then quasi-revenues are given by the area under the \( k \)th value marginal product (inverse factor demand) schedule.

We demonstrate for the two input case although the result generalizes directly. Given the inverse factor demands for water and capital, \( p(w,k) \) and \( q(w,k) \), respectively, Young’s Theorem assures us that \( \frac{\partial p}{\partial k} = \frac{\partial q}{\partial w} \) and the line integral

\[
R = \int_C p(w,k)dw + q(w,k)dk
\]

is independent of path, where \( C \) is any path from \((0,0)\) to \((w^*,k^*)\). In particular, consider the path from \((0,0)\) to \((0,k^*)\), then \((0,k^*)\) to \((w^*,k^*)\). Thus,

\[
R = \int_0^{w^*} p(w,k^*)dw + \int_0^{k^*} q(0,k)dk
\]

and, if water is an weakly essential input, then the integrand in the second integral, and hence the second integral itself, is zero; i.e., the marginal willingness to pay for capital is zero when no water is available. Thus we have

\[
R = \int_0^{w^*} p(w,k^*)dw
\]

as desired.

Appendix B. Demand Estimation

We assume a linear demand function which is consistent with a (quadratic) production function of the form

\[
F(w,k) = Ae(k)w - B[e(k)w]^2 + C
\]

where \( A \) and \( B \) are both positive and \( C \) is of undetermined sign. Thus, the VMP for irrigation water is

\[
p(w,k) = Ae(k)w - 2B[e(k)]^2w
\]
Table 3
Statistical results

<table>
<thead>
<tr>
<th>Test statistic</th>
<th>Significance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{R}^2$</td>
<td>0.71</td>
</tr>
<tr>
<td>Durbin's $h$</td>
<td>-1.1941</td>
</tr>
<tr>
<td>$F_1^*$</td>
<td>17.02282</td>
</tr>
<tr>
<td>$F_2^*$</td>
<td>0.4898</td>
</tr>
</tbody>
</table>

and the VMP for irrigation capital is

$$q(w, k) = Ae'(k)w - 2Be(k)e'(k)w^2$$

Note that the VMP for capital is zero when $w$ is zero; i.e., $q(0,k)$ so that water is a weakly essential input. In the expression for $p$ solve for $w$ to obtain

$$w = A/2Be(k) - p/[2Be(k)]^2$$

We regress $w$ on a number of the variables usually thought to influence water demand and then collapse all statistically significant variables into the constant term. Therefore, analogous to the theoretical demand function derived for $w$ above, the regression is run with adjusted data so that all exogenous variables are divided by $e(k)$ for the respective year and water price (pumping cost) data are divided by $[e(k)]^2$. Recall that the $w$ series was obtained by using reported values for irrigated acreage, crop requirements, and efficiency to generate $w$ values via the water accounting identity (1) of the main text.

The demand for water was estimated as a lagged dependent variable model for the time period 1958–1990. We examined all zero, one-, two- and three-period lag specifications and found the best predictor of water demand to be given by

$$\hat{W} = \frac{289,448}{(70,310)} + \frac{0.4686W_{t-1}}{(0.1248)} - \frac{3147C_{P_{t-1}}}{(5028)} - \frac{3647R_{t-1}}{(1401)} - \frac{2212P_{t-1}}{(811)}$$

where $\hat{W}$ is groundwater quantity demanded, $C_P$ is crop output price, $R$ is rainfall, and $P$ is groundwater input price (pumping cost). Standard errors are shown in parentheses. Specific test statistics are shown in Table 3.26

Seventy-one percent of the variation in groundwater demand was explained by the model as reported by the (adjusted) $R^2$ test statistic. The hypothesis of no autocorrelation could not be rejected since Durbin’s $h$-statistic was $-1.1941$. The estimated equation satisfies the hypotheses of joint explanatory power, since the calculated statistic $F_1^*$ was significant at less than the 1% level. Because pumping cost is largely determined by the price of energy, the Chow test for stability was used. The hypothesis of no structural change could not be rejected, since the calculated statistic $F_2^*$ was not significant. We conclude that the estimated coefficients are stable over the sample period. Since the coefficients on lagged water pumping and rainfall are statistically significant, we collapse them into the intercept

26 Since the coefficient on lagged crop price is insignificant, it is set equal to zero in determining the final numerical demand function below.
by multiplying the coefficient of each variable by the geometric mean of each variable, respectively, over the sample period. As the coefficient on lagged crop price is not significant, it is ignored. The collapsed equation is

\[ w = 348, 393 - 2212p \]

Solving for \( p \) as a function of \( w \) yields

\[ p = 157.748 - 0.000452w. \]

Observing the form for the VMP of water at the beginning of this appendix and using the geometric mean of \( e(k) \) over the sample period (i.e., \( e_0 = 0.61 \)) yields the baseline inverse demand

\[ p = 258.7e_0 - 0.001215e_0^2w. \]

Hence, for any level of investment \( k \), the associated efficiency is \( e(k) \) and the generalized inverse factor demand for water is

\[ p = 258.7e(k) - 0.001215w[e(k)]^2 \]

which corresponds to the theoretical demand \( (p(w,k)) \) derived above.

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