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Benefits from Groundwater Management: Magnitude, Sensitivity, and Distribution

Eli Feinerman and Keith C. Knapp

Empirical estimates of benefits from groundwater management are reported for an area in California with heavy reliance on groundwater supplies. Benefits are quite sensitive to the water demand schedule and interest rate but less sensitive to other parameters. However, in all cases considered the increases in welfare from groundwater management are less than ten percent. Tax revenues received under a system of pump taxes are four to five times as large as the benefits from management. Thus, groundwater users gain under a system of quotas but may suffer substantial welfare losses under pump taxes.

Key words: externalities, groundwater, optimal control, pump taxes, quotas, user cost.

Groundwater supplies roughly 40% of irrigation water used in the western United States (Frederick), with some regions almost completely dependent on underground sources. Concern about the wise use of this resource mounts as water tables drop, energy costs increase, and additional surface supplies become limited and more costly.

As a common property resource, groundwater use is likely to be inefficient without regulation (Milliman; Hirschleifer, DeHaven, Milliman). Individual users have little or no incentive to consider the effects of their withdrawals on other users or on future water levels. Myopic behavior by individual producers thus leads to collective inefficiencies. This proposition may not hold if the aquifer is relatively large in comparison to total groundwater use (Gisser and Sanchez), if the number of users is small and bargaining is relatively easy, if hydraulic conductivities are so small that individual producers face all or most of the consequences of their actions, or if producers temper profit maximization with altruism.

Several studies have investigated alternate management strategies for groundwater basins. A representative sample includes, but is not limited to, Burt; Brown and Deacon; Young and Bredehoeft; Gisser and Sanchez; and Noel, Gardner, and Moore. However, relatively little attention has focused on the benefits of groundwater management. Such benefits have been estimated for only a few basins, no systematic analysis of their sensitivity to various parameters has been reported, and the distributional consequences of various management strategies have not been evaluated. These are important issues since users can be expected to resist any management scheme from which they do not receive substantial benefits.

In this paper we investigate the magnitude of benefits from groundwater management (i.e., control of quantities extracted), their sensitivity to various parameters, and related welfare effects on groundwater users. A single-cell aquifer is assumed. Formulas are derived for the present value of annual net benefits under a general linear decision rule for groundwater withdrawals. With a linear water demand curve, this decision rule can be used to simulate groundwater use under alternate control strategies. The formulas are applied to data from Kern County, California. The results illustrate that benefits are quite sensitive to some parameters but not to others and that the management form (quotas or pump taxes) has a dramatic effect on users' welfare.

Previous Estimates of Groundwater Management Benefits

In an early study of Arizona groundwater management, Kelso demonstrated the sen-

Eli Feinerman is a visiting agricultural economist, and Keith C. Knapp is an assistant professor of resource economics, both at the University of California, Riverside.

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sitivity of the benefits of groundwater management to the interest rate. He argued that growers would realize net benefits only if real interest rates were less than 4-1/4%. A similar study by Renshaw examined groundwater regulation on the Texas High Plains. Renshaw compared the case of no regulation with a policy which reduced groundwater pumping by 50%. Assuming a real interest rate of 5%, the latter strategy would have resulted in losses of $124 per acre of farmland.

Bredehoeft and Young simulated the impacts of alternative policies on a hypothetical aquifer. They found that the net benefits of groundwater management could amount to over $100 per acre but noted that these benefits would decline with increases in the interest rate or increases in the yield coefficient of the aquifer. In a second paper, Young and Bredehoeft applied a similar simulation model to a stretch of the South Platte River in Colorado. With an infinite time horizon and a real interest rate of 5%, their results suggest benefits of approximately $102 per acre of irrigated cropland net of administrative costs.

Howitt calculated the benefits of groundwater management for four areas in California. Management was assumed to begin at the date when the optimal steady-state water level was reached, and benefits at that time ranged from a low of $152.85/acre to a high of $453.52/acre. Corresponding present values in 1979 ranged from $3.84/acre to $65.54/acre. Gisser and Sanchez and Noel, Gardner, and Moore examined groundwater management using dynamic optimization models. Numerical calculations in Gisser and Sanchez for the Pecos basin, New Mexico, suggest that groundwater management would yield zero benefits.[1] On the other hand, Noel, Gardner, and Moore estimated benefits totaling $53 million from optimal groundwater management in Yolo County, California. With 267,000 acres of irrigated cropland in 1978 (1978 Census of Agriculture) this implies benefits of roughly $200 per acre of irrigated cropland.

While different methods and assumptions were employed in these studies, several general conclusions emerge. First, the early studies by Kelso and Renshaw show that ad hoc groundwater management policies may result in economic loss. Second, even under optimal management the possibility of negligible benefits from groundwater management exists. It also seems clear that the benefits from groundwater management may differ from one basin to the next depending on the economic and hydrologic parameters. Thus, it is important to investigate in detail the sensitivity of groundwater management benefits to different parameters.

The Model

Consider an agricultural area relying on a single-cell aquifer for part of its water supply. Withdrawals in time period t are denoted w_t, pumping lifts by h_t, and net recharge to the aquifer from all sources except groundwater return flows by r. Under these assumptions annual pumping lifts are given by

$$h_{t+1} = h_t + \frac{(1-\theta)w_t - r}{As}, \tag{1}$$

where θ is the fraction of applied groundwater returning to the aquifier ($0 \leq \theta < 1$), A is the area of the aquifer, s the specific yield, and the initial lift h_1 is given.

Benefits from groundwater withdrawals are assumed to be given by the area under a linear demand curve. Pumping costs are eh_tw_t, where e denotes the cost of energy needed to lift one acre-foot of water one foot.[2] Annual net benefits from groundwater use are then

$$NB_t = aw_t - \frac{b}{2}w_t^2 - eh_tw_t, \tag{2}$$

where a and b are the intercept and slope, respectively, of the groundwater demand curve.

Groundwater withdrawals are assumed to be a linear function of the lift,

$$w_t = \beta_0 - \beta_1 h_t, \tag{3}$$

where $\beta_0 > 0$ and $\beta_1 > 0$. Appropriate specification of β_0 and β_1 allows simulation of (a) no management (competition) and (b) alternate control strategies. Additional restrictions on the model are that $w_t \geq 0$ and $0 \leq h_t \leq h^{max}$,

[1] Gisser and Sanchez assume an interest rate of 10%. As we show later, the benefits from management are extremely sensitive to the interest rate, thus a smaller interest rate may have resulted in positive benefits. An anonymous reviewer has also pointed out that the relative storativity (As/r) is much greater for the basin considered in their paper than that considered here.

[2] We have not considered the costs of capital items (pumps and wells); therefore, our estimates of benefits from groundwater management are low to the extent that management will reduce these costs.

where h^{max} is the maximum pumping lift determined by the depth of the aquifer.

Substituting (3) into (1) and rearranging yields

$$(4) \qquad h_{t+1} = C_0 + C_1 h_t,$$

where

$$C_0 = \frac{(1-\theta)\,\beta_0 - r}{As} \text{ and}$$

$$C_1 = 1 + \frac{\beta_1(\theta - 1)}{As}.$$

It is then easy to check that

$$(5) \quad h_t = \frac{C_0}{1 - C_1} + C_1^{t-1}\left(h_1 - \frac{C_0}{1 - C_1}\right)$$

for $t = 1, \ldots, \infty$.

From (1) and (3), the steady-state withdrawals and pumping lifts are

$$w_{ss} = \frac{r}{1 - \theta} \text{ and } h_{ss} = \frac{\beta_0 - w_{ss}}{\beta_1},$$

respectively. If $|C_1| < 1$, then pumping lifts converge to h_{ss}, and so $0 < h_{ss} < h^{max}$ implies that $0 \leq h_t \leq h^{max}$ for all t. In addition, if $\beta_0/\beta_1 \geq \max(h_1, h_{ss})$, then $w_t \geq 0$ for all t. Under these conditions the system is completely defined by (2), (3), and (5), and a formula for the present value of net benefits over an infinite horizon may be derived.

Using (2) and (3) the net benefits from groundwater withdrawals in period t are given by

$$(6) \qquad NB_t = H_0 + H_1 h_t + H_2 h_t^2,$$

with

$$H_0 = a\beta_0 - \frac{b}{2}\beta_0^2$$

$$H_1 = -a\beta_1 + b\beta_0\beta_1 - e\beta_0$$

$$H_2 = \frac{-b\beta_1^2}{2} + e\beta_1.$$

The present value of annual net benefits $(\sum_{t=1}^{\infty} \alpha^t NB_t)$ is then given by the expression:

$$(7) \qquad \frac{\alpha K_0}{1 - \alpha} + \frac{\alpha K_1}{1 - \alpha C_1} + \frac{\alpha K_2}{1 - \alpha C_1^2},$$

where

$$K_0 = H_0 + H_1\left(\frac{C_0}{1 - C_1}\right) + H_2\frac{C_0^2}{(1 - C_1)^2}$$

$$K_1 = \left(h_1 - \frac{C_0}{1 - C_1}\right)\left[H_1 + 2H_2\left(\frac{C_0}{1 - C_1}\right)\right]$$

$$K_2 = H_2\left(h_1 - \frac{C_0}{1 - C_1}\right)^2,$$

and the discount factor α equals $1/(1 + i)$, with i the annual real interest rate.

If the aquifer would be exhausted for given β_0 and β_1 (h_{ss} is greater than the depth of the aquifer) or the other conditions are not met, then formula (7) is not valid and other calculations must be used. The formula does hold for all empirical situations considered in this paper. The present value of annual net benefits from groundwater withdrawal is calculated under control and no control (competition). The difference represents the benefits from groundwater management.

Empirical Specification

The model is applied to Kern County, California. This is a critical area for groundwater management since there is a heavy reliance on groundwater to meet water demands (primarily agricultural). In addition, overdraft levels typically have been severe. Data were collected from publications of the California Department of Water Resources (DWR), the Kern County Water Agency (KCWA), and other sources. The assumed parameter values are summarized in table 1. Specific sources are discussed below.

Area of the aquifer and an average specific yield were calculated from detailed data in DWR (1977). An estimate of θ was obtained from the same source. Recharge to the aquifer from all sources except groundwater return flows is denoted r and calculated by

$$r = (1 - \gamma + \theta\gamma)I + \bar{r},$$

where I is mean annual surface inflows to Kern County, γ is the fraction of surface inflows diverted to irrigation, and $\bar{r}$ is recharge to the aquifer from other sources including underground flows. Mean annual surface inflows (I) were calculated as the sum of the average annual surface inflows of the three major streams entering Kern County—Friant Kern Canal (FKC), Kern River (KR), and the State Water Project (SWP). Water flows from the FKC (282,000 A.F.) and the KR (668,000 A.F.) were calculated from historical data in

Table 1. Parameter Values for Kern County, California

Parameter	Description	Value
A	aquifer area	1.29 million acres
s	specific yield	.10
$\bar{r}$	natural recharge	52,000 a-f/yr
h_1	initial lift	220 feet
I	average annual surface inflows	1.90 maf/yr
γ	fraction of surface inflows diverted to irrigation	.7
θ	deep percolation coefficient	.2
e	energy cost	\$.09/a-f/foot
a'	water demand intercept	\$92.7/a-f
b'	water demand slope	\$.0000175/a-f^2
A_f	acres farmed	1.004 million acres
i	real interest rate	.05

DWR (1977) and KCWA (1979). The estimated availability of SWP supplies (950,000 A.F.) to Kern County was taken from KCWA (1979). The value $\bar{r}$, which is composed of average annual subsurface inflow (17,000 A.F.) and minor streams (35,000 A.F.), was obtained from the same (latter) source.[3] An estimate of γ was calculated from data in KCWA (1980) and previous issues. It was confirmed by a local soil and irrigation consultant. The initial pumping lift, h_1, was also taken from the same source.

The per acre demand for water was estimated from the results of Moore and Hedges. The demand curve was adjusted for inflation and then aggregated to obtain a total demand curve for water in Kern County. Surface water was assumed to be used in preference to groundwater when available. The intercept and slope of the groundwater demand function are then

$$a = a' - b\gamma I \text{ and } b = b'$$

where a' and b' are the intercept and slope, respectively, of the Kern County water demand curve. Energy costs of pumping were calculated assuming 1.024 kilowatt-hours per acre-foot per foot of lift (KCWA 1979), an average pumping plant efficiency of 60% (DWR 1981) and electricity prices of \$.05 per kilowatt-hour (Christensen, Harrison, Kimbell). The real rate of interest was assumed to be 5%.

Three different linear decision rules were simulated initially. The first simulates no management (competition); the second is the first-order approximately optimal decision rule first proposed by Burt; the third is an approximately optimal decision rule which assumes that future pumping levels are equal to steady-state withdrawals.

Without management, groundwater users have little incentive to consider the effects of their pumping on other users or on future water levels (Wetzel). It is therefore reasonable to assume that, in an unregulated basin with many users, water is pumped until marginal benefits equal marginal pumping costs:

$$a - bw_t = eh_t.$$

This can be rearranged to obtain a linear decision rule for w_t with

$$\beta_0 = a/b \quad \text{and} \quad \beta_1 = e/b.$$

Optimal control of groundwater withdrawals implies that water is pumped until marginal benefits equal marginal pumping costs plus marginal user cost. (Marginal user cost is the reduction in discounted future net benefits from a withdrawal of one additional unit in the current period.) Calculation of marginal user cost requires knowledge of future optimal pumping levels. These can be determined by dynamic programming (Burt) or Pontryagin's maximum principle for continuous time (Brown). However, one approximation is to assume that future pumping is just equal to current pumping. In this case marginal user cost is $ew_t\,(1 - \theta)/Asi$, and w_t is the solution to

$$a - bw_t = eh_t + \frac{ew_t(1 - \theta)}{Asi}.$$

This can be rearranged to yield w_t as a linear function of h_t with $\beta_0 = a/[b + e(1 - \theta)/Asi]$ and $\beta_1 = e/[b + e(1 - \theta)/Asi]$. This decision rule is analogous to the approximately optimal

[3] Underground flows are small relative to total water use. Hence, we have not considered the spatial externalities between Kern County and its neighbors.

decision rule first proposed by Burt. We call this Rule 1.

A second approximation is to assume that future pumping levels are the steady-state amount. In this case, marginal user costs are er/Asi, and w_t is the solution to

$$a - bw_t = eh_t + \frac{er}{Asi},$$

which can be arranged to express w_t as a linear function of h_t, with $\beta_0 = \frac{a}{b} - \frac{er}{Asib}$ and $\beta_1 = \frac{e}{b}$. This is Rule 2.

Both decision rules result in approximations to the optimal time path. It can be verified that pumping lifts under either rule converge to the optimal steady-state level. The marginal user cost in Rule 1 assumes that future extractions are equal to the current level. If the initial lift is less than the optimal steady state, then future withdrawals are less than current ones. Hence, the marginal user cost in Rule 1 is overstated compared to a fully optimal regime. On the other hand, the marginal user cost in Rule 2 assumes that future withdrawals equal withdrawals in the steady state. Under the assumption of an initial lift less than the optimal steady state, future withdrawals are greater than steady-state withdrawals during the transition; and so the marginal user cost in Rule 2 understates the true marginal user cost. If initial groundwater levels are lower than the optimal steady state, then the opposite result occurs—Rule 1 understates marginal user cost and Rule 2 overstates it. In either case, the optimal marginal user cost lies between those of Rule 1 and Rule 2.

Results

With parameters as specified in table 1, the steady-state pumping lifts are 556 feet and 418 feet under competition and optimal control, respectively. The present value of net benefits from groundwater withdrawals are \$853 per irrigated acre with competition, \$969 per acre with Rule 1, and \$963 per acre with Rule 2. The benefits from groundwater management in Kern County are \$116 per acre for Rule 1 and \$110 per acre for Rule 2. These results compare favorably with estimates for other basins. Because the two control rules yield similar results, only Rule 1 will be considered in the subsequent analysis.

Table 2 shows additional calculations under plausible alternative values for each parameter. The first three columns detail the specific changes, while the fourth and fifth give discounted net benefits from groundwater use under competition and control, respectively. Benefits from groundwater management are

Table 2. Sensitivity Analysis

			P.V. Net Benefits ($/acre)				
Symbol	Description	Value	Competition	Optimal Control	Benefits from GWM ($/Acre)	Elasticity	PVPT ($/Acre)
As	Area times	100,000 acres	780	931	151	−1.04	579
	specific yield	150,000 acres	895	994	99		520
$\bar{r}$	Underground	32,000 acre feet	846	961	115	0.03	539
	recharge	72,000 acre feet	859	977	118		548
h_1	Initial	180 feet	959	1,087	128	−0.52	609
	lift	260 feet	752	858	106		481
I	Surface	1,600,000 acre feet	919	1,035	116	0.03	580
	inflow	2,200,000 acre feet	791	908	117		509
γ	Diversion	0.6	1,002	1,143	141	−1.40	641
	coefficient	0.8	715	809	94		454
θ	Return flow	0.1	751	860	109	0.10	507
	coefficent	0.3	978	1,099	121		580
e	Energy	0.06 $/acre feet/feet	1,204	1,294	90	0.57	595
	cost	0.12 $/acre feet/feet	616	748	132		471
a'	Demand	104.7 $/acre feet	1,234	1,390	156	2.40	779
	intercept	80.7 $/acre feet	544	626	82		351
b	Demand	0.000010 $/acre feet^2	1,368	1,654	286	−1.63	1,142
	slope	0.000025 $/acre feet^2	519	570	51		269
i	Interest	0.03	1,177	1,502	325	−1.77	1,022
	rate	0.07	677	733	56		350

given in the sixth column. (Columns 7 and 8 are described later.)

As table 2 shows, the benefits of groundwater management decrease as the aquifer area or the specific yield increases. This corresponds to the results in Gisser and Sanchez. The effect of withdrawals on pumping lifts decrease as either A or s increases. Because the externalities imposed by one user on others are less, we expect benefits from management to decrease. Management benefits increase as recharge, surface inflow, deep percolation, and energy costs increase. Thus, groundwater management becomes increasingly desirable as real energy costs increase. Benefits decrease as the initial lift increases, implying that management should be started as early as possible. Benefits increase substantially if the water demand curve shifts up or if it becomes more elastic. Benefits are much greater under a low interest rate than a high one.

To analyze the relative sensitivity of various parameters, we computed an arc elasticity for management benefits. These elasticities are reported in the seventh column of table 2 and show the percentage change in management benefits from a one percent change in the parameter value. The results suggest that benefits are quite sensitive to the demand function and interest rate, moderately sensitive to As and γ, and relatively insensitive to other parameters. For groundwater management, accurate estimation of the economic parameters is at least as important as accurate estimation of the hydrologic parameters.

We also investigated the case of stochastic surface supplies. Surface supplies were assumed to be independently and identically distributed normal random variables with mean and standard deviation of 1.9 million acre feet per year and .55 million acre feet per year, respectively. Using Rule 1, the probability distribution of the lift converges to a steady-state distribution with constant variance and a mean equal to the deterministic steady state. There is a 99% probability of being within 5% of the mean. Expected benefits from groundwater management were found to be \$117 per acre compared to \$116 per acre under certainty. Since this difference is insignificant, we did not pursue the uncertainty case further.

Distribution

If groundwater extractions are controlled by a system of quotas, then all management benefits accrue to pumpers. However, if extractions are controlled by pump taxes without rebates, then at least some benefits will accrue to nonusers. Whether users will be better or worse off with pump taxes compared to no management is not obvious a priori. Although they pay for water that was previously free, future pumping costs will be lower. Milliman, and Jacquette and Moore state that groundwater users will be worse off. However, they provide no proof or empirical evidence. In the context of static common property resource models, Weitzman, Sadka, and Baumol and Oates show that users of the resource will suffer welfare losses under efficiency-inducing tax schemes. We now illustrate that this result also holds for the dynamic groundwater model used here and that the losses are substantial.

Pump taxes are determined by the differences between $a - bw_t$, the marginal benefit of groundwater withdrawals determined by the linear decision rule, and eh_t, the marginal pumping cost. Tax revenues in period t, PT_t, are then given by

$$PT_t = H_0 + H_1h_t + H_2h_t^2, \tag{8}$$

with

$$H_0 = a\beta_0 - \beta_0^2b$$
$$H_1 = 2\beta_0\beta_1b - e\beta_0 - a\beta_1$$
$$H_2 = e\beta_1 - \beta_1^2b;$$

and the present value of pump tax revenues $\left(\sum_{t=1}^{\infty} a^tPT_t\right)$ can then be calculated from (7).

The results are reported in the last column of table 2. The present value of pump tax revenues range from \$269 per acre to \$1142 per acre. These tax revenues are three to six times as large as the benefits. Because users will experience substantial losses under pump taxes, they can be expected to resist their imposition vigorously.

There are several ways in which user losses under pump taxes can be reduced. One option is for part or all of the tax revenues to be rebated back to the users. However, there are potential difficulties with such schemes. If users are to perceive gains from management, then they must receive back approximately what they paid out. If rebates are related to quantities pumped, then the incentive effect of the tax is lost. If rebates are related to some other variable, such as total acreage in production, then farmers pumping large quantities of water relative to farm size will lose relative to farmers pumping smaller quantities per acre.

Another option is to allow pump taxes to be a function of the quantity of water actually pumped. This option was first proposed by Milliman and is discussed by Wetzel and Jaquette and Moore. Like quotas, variable pump taxes allow groundwater users to capture most or all of the benefits of groundwater management without rebates. In addition, variable taxes permit more flexibility than quotas by allowing pumpers to expand withdrawals beyond the optimal quantity if they are willing to bear all extraction costs.

Conclusions

Either quotas or pump taxes can be used to achieve efficient groundwater withdrawals in the aggregate. However, this paper shows that there are dramatic differences in the distributional consequences. Groundwater users gain under quotas but suffer heavy losses under taxes. Under a constant pump tax scheme, losses from tax revenues paid by users were three to six times as large as the benefits from management. Either rebates or variable pump tax schedules could mitigate the distributional consequences; however, the latter seems the most promising.

The sensitivity analysis provides alternate estimates of benefits from management in Kern County. More generally, it suggests how management benefits will change as economic and water supply conditions change. It also provides evidence about the relative sensitivity of various parameters. Benefits from management can be expected to increase as energy costs rise. If the real value of agricultural products increases, then the demand curve for agricultural water use will shift up, increasing the benefits from management. Benefits are extremely sensitive to the interest rate and the water demand curve. For example, a decrease in the discount rate from 5% to 3% implied a threefold increase in management benefits. If accurate estimates of management benefits are to be obtained, these parameters must be carefully estimated.

Benefits from groundwater management were calculated to be $116 per irrigated acre in Kern County. This compares favorably with estimates for other basins. It represents a 14% increase in the net benefits from groundwater use compared to no regulation and a 6% increase in the net benefits from both ground and surface water use.[4] Similar calculations were made for the parameter values in table 2. In each case the increase in net benefits of ground and surface water use was less than 10%.

The relevant guideline for instituting groundwater management is obviously that benefits exceed the costs. We have not attempted to estimate the costs of management; however, the results do raise the possibility (first suggested by Gisser and Sanchez) that the gains from management are not very large when compared to net benefits of combined surface and groundwater use already existing. There are enough difficulties with this analysis, however, that we take this only as a tentative hypothesis for further research. Substantial uncertainties exist about some of the parameters (water demand and discount rate) to which benefits are most sensitive. The single-cell model overlooks the considerable complexity of the aquifer, water quality issues have not been addressed, and we have not attempted to estimate capital costs associated with groundwater pumping. Estimates of groundwater management benefits will be substantially improved as these and other considerations are accounted for.

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[4] The average price of surface water in Kern County is assumed to be $32 per acre-foot (Howitt, Mann, and Vaux).

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